US007864822B2

(12) **United States Patent**
Bouma et al.

(10) **Patent No.: US 7,864,822 B2**
(45) **Date of Patent: Jan. 4, 2011**

(54) **PROCESS AND APPARATUS FOR A WAVELENGTH TUNING SOURCE**

(75) Inventors: **Brett Eugene Bouma**, Quincy, MA (US); **Seok-Hyun (Andy) Yun**, Cambridge, MA (US); **Wang-Yuhl (William) Oh**, Cambridge, MA (US); **Johannes F. De Boer**, Amstelveen (NL); **Guillermo J. Tearney**, Cambridge, MA (US)

(73) Assignee: **The General Hospital Corporation**, Boston, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **12/369,556**

(22) Filed: **Feb. 11, 2009**

(65) **Prior Publication Data**

US 2009/0257461 A1 Oct. 15, 2009

Related U.S. Application Data

(62) Division of application No. 11/867,953, filed on Apr. 11, 2008, now Pat. No. 7,724,786, which is a division of application No. 10/861,179, filed on Jun. 4, 2004, now Pat. No. 7,519,096.

(60) Provisional application No. 60/476,600, filed on Jun. 6, 2003, provisional application No. 60/514,769, filed on Oct. 27, 2003.

(51) **Int. Cl.**
H01S 3/10 (2006.01)

(52) **U.S. Cl.** **372/20**; 372/28; 372/32

(58) **Field of Classification Search** 372/20, 372/28
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,639,999	A	2/1987	Daniele
4,763,977	A	8/1988	Kawasaki et al.
4,940,328	A	7/1990	Hartman
4,984,888	A	1/1991	Tobias et al.
5,202,931	A	4/1993	Bacus et al.
5,251,009	A	10/1993	Bruno
5,281,811	A	1/1994	Lewis

(Continued)

FOREIGN PATENT DOCUMENTS

CN	1550203	12/2004
JP	20030035659	2/2003
WO	2005082225	9/2005

OTHER PUBLICATIONS

Office Action dated Jul. 7, 2010 for U.S. Appl. No. 11/624,277.
Montag Ethan D., "Parts of the Eye" online textbook for JIMG 774: Vision & Psycophysics, download on Jun. 23, 2010 from http://www.cis.rit.edu/people/faculty/montag/vandplite/pp./chap_8/ch8p3.html.
Office Action dated Jul. 16, 2010 for U.S. Appl. No. 11/445,990.
Office Action dated Jul. 20, 2010 for U.S. Appl. No. 11/625, 135.
Office Action dated Aug. 5, 2010 for U.S. Appl. No. 11/623,852.

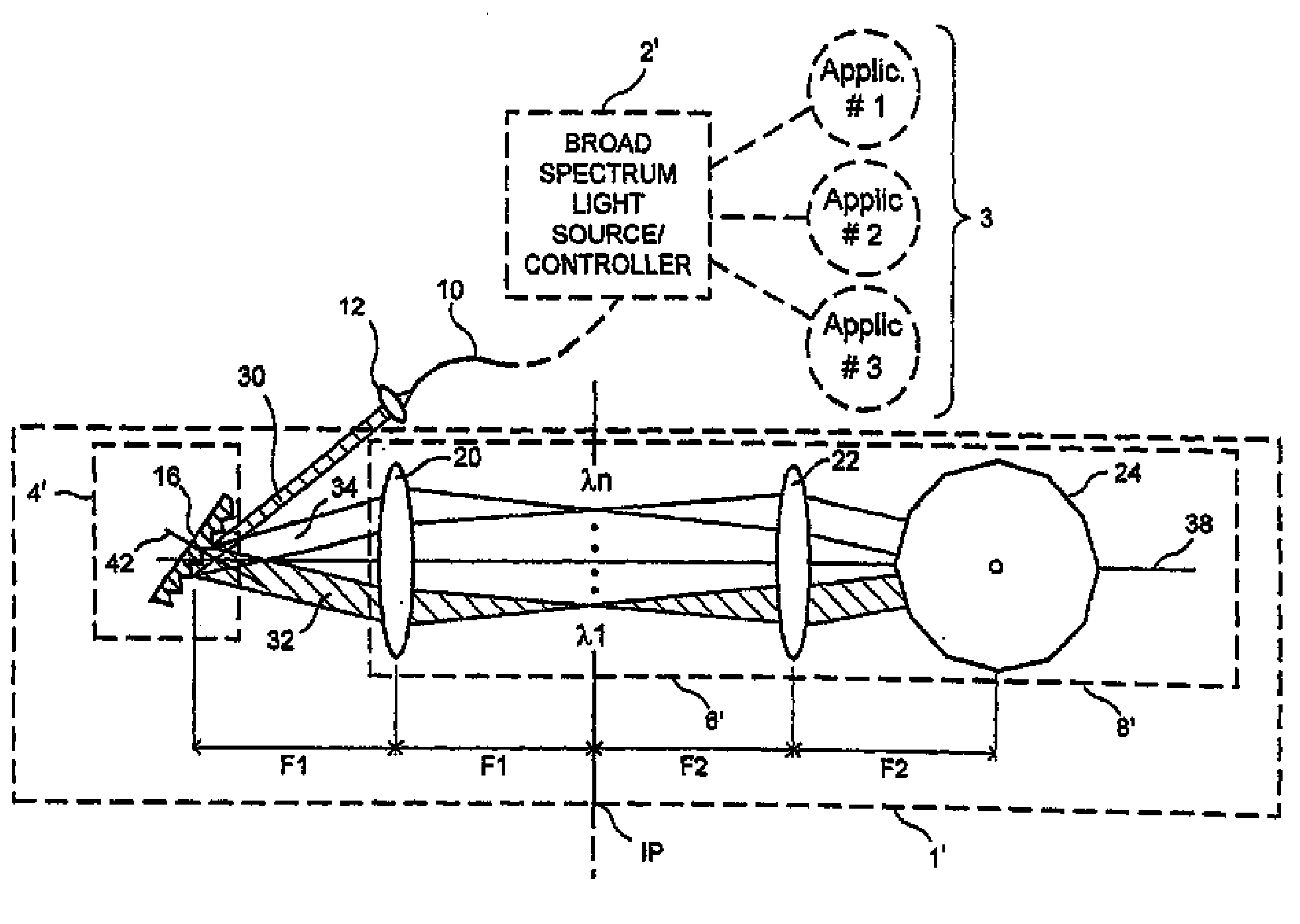
(Continued)

Primary Examiner—Dung T Nguyen
(74) *Attorney, Agent, or Firm*—Dorsey & Whitney LLP

(57) **ABSTRACT**

An apparatus and source arrangement for filtering an electromagnetic radiation can be provided which may include at least one spectral separating arrangement configured to physically separate one or more components of the electromagnetic radiation based on a frequency of the electromagnetic radiation. The apparatus and source arrangement may also have at least one continuously rotating optical arrangement which is configured to receive at least one signal that is associated with the one or more components. Further, the apparatus and source arrangement can include at least one beam selecting arrangement configured to receive the signal.

6 Claims, 16 Drawing Sheets



U.S. PATENT DOCUMENTS

5,404,415	A	4/1995	Mori et al.	
5,424,827	A	6/1995	Horwitz et al.	
5,522,004	A	5/1996	Djupsjobacka et al.	
5,565,983	A	10/1996	Barnard et al.	
5,801,831	A	9/1998	Sargoytchev et al.	
5,836,877	A	11/1998	Zavislan et al.	
5,994,690	A	11/1999	Kulkarni et al.	
6,007,996	A	12/1999	McNamara et al.	
6,010,449	A	1/2000	Selmon et al.	
6,078,047	A *	6/2000	Mittleman et al.	250/338.1
6,107,048	A	8/2000	Goldenring et al.	
6,249,630	B1	6/2001	Stock et al.	
6,301,048	B1	10/2001	Cao et al	
6,437,867	B2	8/2002	Zeylikovich et al.	
6,441,892	B2	8/2002	Xiao et al.	
6,441,959	B1	8/2002	Yang et al.	
6,485,413	B1	11/2002	Boppart et al.	
6,593,101	B2	7/2003	Richards-Kortum et al.	
6,611,833	B1	8/2003	Johnson et al.	
6,654,127	B2	11/2003	Everett et al.	
6,657,730	B2	12/2003	Pfau et al.	
6,692,430	B2	2/2004	Adler	
6,900,899	B2	5/2005	Nevis	
6,961,123	B1	11/2005	Wang et al.	
6,996,549	B2	2/2006	Zhang et al.	
7,027,633	B2	4/2006	Foran et al.	
7,072,047	B2	7/2006	Westphal et al.	
7,075,658	B2	7/2006	Izatt et al.	
7,113,288	B2	9/2006	Fercher	
7,113,625	B2	9/2006	Watson et al.	
7,139,598	B2	11/2006	Hull et al.	
7,177,027	B2	2/2007	Hirasawa et al.	
7,272,252	B2	9/2007	De La Torre-Bueno et al.	
7,342,659	B2	3/2008	Horn et al.	
7,458,683	B2	12/2008	Chernyak et al.	
7,530,948	B2	5/2009	Seibel et al.	
7,646,905	B2	1/2010	Guittet et al.	
7,664,300	B2	2/2010	Lange et al.	
7,782,464	B2	8/2010	Mujat et al.	
2002/0024015	A1	2/2002	Hoffmann et al.	
2002/0086347	A1	7/2002	Johnson et al.	
2002/0122182	A1	9/2002	Everett et al.	
2003/0013973	A1	1/2003	Georgakoudi et al.	
2003/0053673	A1	3/2003	Dewaele et al.	
2003/0067607	A1	4/2003	Wolleschensky et al.	
2003/0165263	A1	9/2003	Hamer et al.	
2003/0174339	A1	9/2003	Feldchtein et al.	
2004/0076940	A1	4/2004	Alexander et al.	
2004/0126048	A1	7/2004	Dave et al.	
2004/0126120	A1	7/2004	Cohen et al.	
2004/0189999	A1	9/2004	De Groot et al.	
2004/0239938	A1	12/2004	Izatt	
2004/0246583	A1	12/2004	Mueller et al.	
2005/0036150	A1	2/2005	Izatt et al.	
2005/0059894	A1	3/2005	Zeng et al.	
2005/0065421	A1	3/2005	Burckhardt et al.	
2005/0128488	A1	6/2005	Milen et al.	
2006/0033923	A1	2/2006	Hirasawa et al.	
2006/0164639	A1	7/2006	Horn et al.	
2006/0171503	A1	8/2006	O'Hara et al.	
2007/0038040	A1	2/2007	Cense et al.	
2007/0086017	A1	4/2007	Buckland et al.	
2007/0188855	A1	8/2007	Milen et al.	
2007/0236700	A1	10/2007	Yun et al.	
2007/0258094	A1	11/2007	Izatt et al.	
2008/0007734	A1	1/2008	Park et al.	
2008/0097225	A1	4/2008	Milen et al.	
2008/0204762	A1	8/2008	Izatt et al.	
2009/0273777	A1	11/2009	Yun et al.	
2010/0086251	A1	4/2010	Xu et al.	
2010/0150467	A1	6/2010	Zhao et al.	

FOREIGN PATENT DOCUMENTS

JP	20040056907	2/1992

OTHER PUBLICATIONS

Chinese office action dated Aug. 4, 2010 for CN 200780005949.9.

Chinese office action dated Aug. 4, 2010 for CN 200780016266.3.

Zhang et al., "Full Range Polarization-Sensitive Fourier Domain Optical Coherence Tomography" Optics Express, Nov. 29, 2004, vol. 12, No. 24.

Office Action dated Aug. 27, 2010 for U.S. Appl. No. 11/569,790.

Office Action dated Aug. 31, 2010 for U.S. Appl. No. 11/677,278.

Office Action dated Sep. 3, 2010 for U.S. Appl. No. 12/139,314.

R. Haggitt et al., "Barrett's Esophagus Correlation Between Mucin Histochemistry, Flow Cytometry, and Histological Diagnosis for Predicting Increased Cancer Risk," Apr. 1988, American Journal of Pathology, vol. 131, No. 1, pp. 53-61.

R.H. Hardwick et al., (1995) "c-erbB-2 Overexpression in the Dysplasia/Carcinoma Sequence of Barrett's Oesophagus," Journal of Clinical Pathology, vol. 48, No. 2, pp. 129-132.

Polkowski et al, (1998) Clinical Decision making in Barrett's Oesophagus can be supported by Computerized Immunoquantitation and Morphometry of Features Associated with Proliferation and Differentiation, Journal of pathology, vol. 184, pp. 161-168.

J.R. Turner et al., MN Antigen Expression in Normal Preneoplastic, and Neoplastic Esophagus: A Clinicopathological Study of a New Cancer-Associated Biomarker,: Jun. 1997, Human Pathology, vol. 28, No. 6, pp. 740-744.

D.J. Bowery et al., (1999) "Patterns of Gastritis in Patients with Gastro-Oesophageal Reflux Disease,", Gut, vol, 45, pp. 798-803.

O'Reich et al., (2000) "Expression of Oestrogen and Progesterone Receptors in Low-Grade Endometrial Stromal Sarcomas,", British Journal of Cancer, vol. 82, No. 5, pp. 1030-1034.

M.I. Canto et al., (1999) "Vital Staining and Barrett's Esophagus," Gastrointestinal Endoscopy, vol. 49, No. 3, Part 2, pp. S12-S16.

S. Jackle et al., (2000) "In Vivo Endoscopic Optical Coherence Tomography of the Human Gastrointestinal Tract-Toward Optical Biopsy," Encoscopy, vol. 32, No. 10, pp. 743-749.

E. Montgomery et al., "Reproducibility of the Diagnosis of Dysplasia in Barrett Esophagus: a Reaffirmation," Apr. 2001, Human Pathology, vol. 32, No. 4, pp. 368-378.

H. Geddert et al., "Expression of Cyclin B1 in the Metaplasia-Dysphasia -Carcinoma Sequence of Barrett Esophagus," Jan. 2002, Cancer, vol. 94, No. 1, pp. 212-218.

P. Pfau et al., (2003) "Criteria for the Diagnosis of Dysphasia by Endoscopic Optical Coherence Tomography," Gastrointestinal Endoscopy, vol. 58, No. 2, pp. 196-2002.

R. Kiesslich et al., (2004) "Confocal Laser Endoscopy for Diagnosing Intraepithelial Neoplasias and Colorectal Cancer in Vivo," Gastroenterology, vol. 127, No. 3, pp. 706-713.

X. Qi et al., (2004) "Computer Aided Diagnosis of Dysphasia in Barrett's Esophagus Using Endoscopic Optical Coherence Tomography," SPIE, Coherence Domain Optical Methods and Optical Coherence Tomography in Biomedicine VIII. Proc. of Conference on., vol. 5316, pp. 33-40.

Seltzer et al., (1991) "160 nm Continuous Tuning of a MQW Laser in an External Cavity Across the Entire 1.3 μm Communications Window," Electronics Letters, vol. 27, pp. 95-96.

Office Action dated Jan. 25, 2010 for U.S. Appl. No. 11/537,048.

International Search Report dated Jan. 27, 2010 for PCT/US2009/050553.

International Search Report dated Jan. 27, 2010 for PCT/US2009/047988.

International Search Report dated Feb. 23, 2010 for U.S. Appl. No. 11/445,131.

Office Action dated Mar. 18, 2010 of U.S. Appl. No. 11/844,454.

Office Action dated Apr. 8, 2010 of U.S. Appl. No. 11/414,564.

Japanese Office Action dated Apr. 13, 2010 for Japanese Patent application No. 2007-515029.

International Search Report dated May 27, 2010 for PCT/US2009/063420.

Office Action dated May 28, 2010 for U.S. Appl. No. 12/015,642.

Office Action dated Jun. 2, 2010 for U.S. Appl. No. 12/112,205.

* cited by examiner

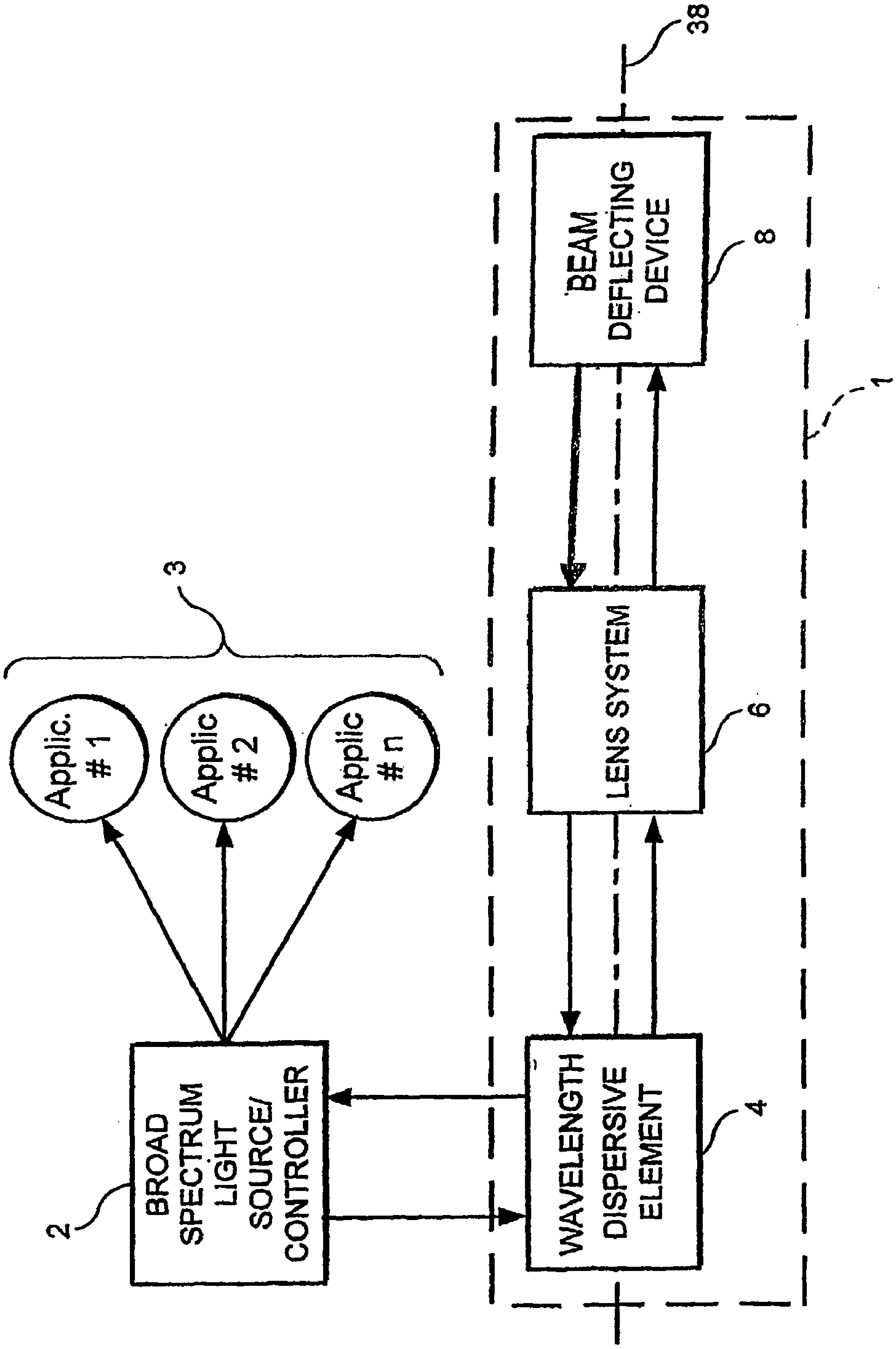

BROAD SPECTRUM LIGHT SOURCE/ CONTROLLER
2
Applic. # 1
Applic # 2
Applic # n
3
WAVELENGTH DISPERSIVE ELEMENT
4
LENS SYSTEM
6
BEAM DEFLECTING DEVICE
8
38
1

FIG. 1A

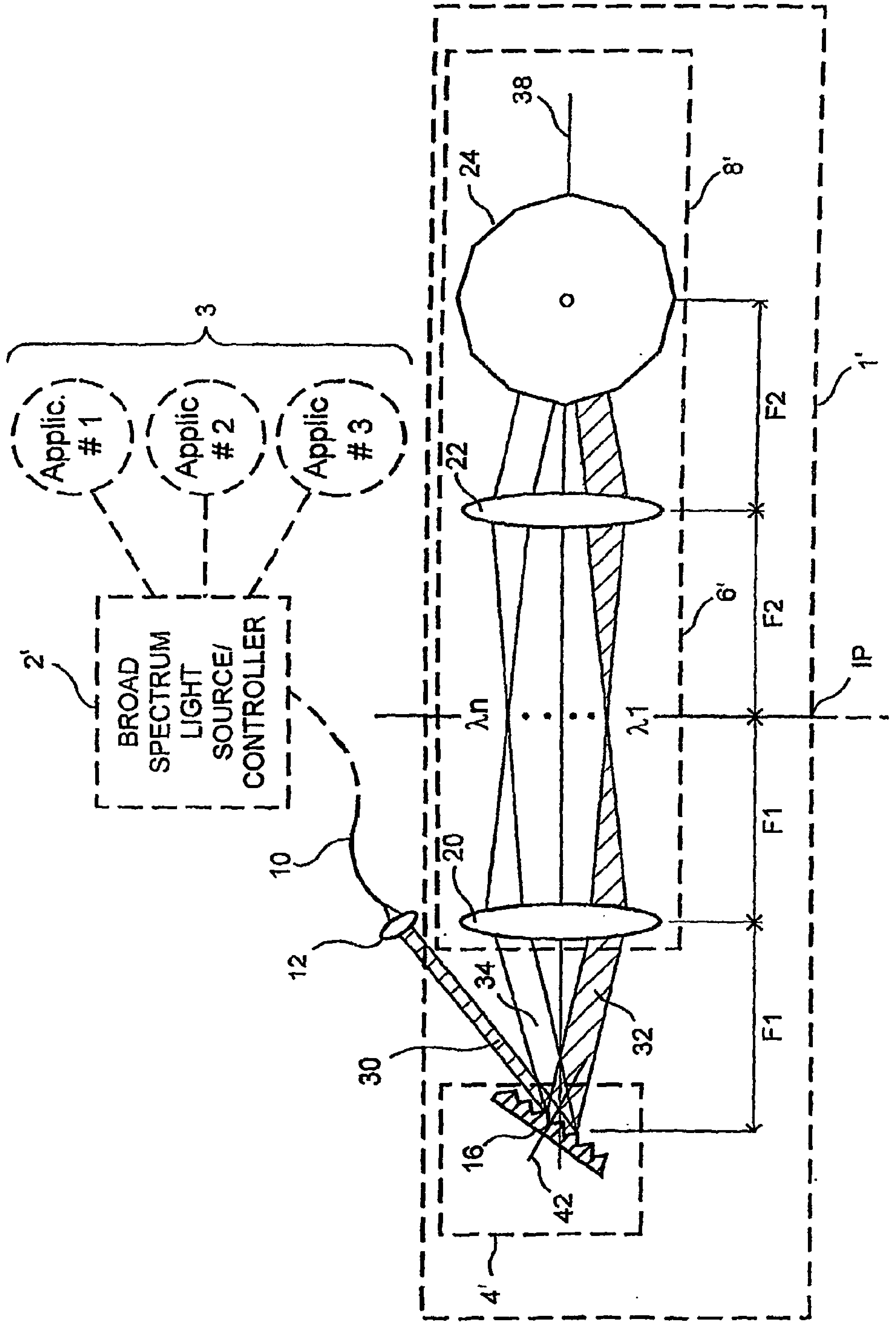

3
Applic. #1
Applic #2
Applic #3
2'
BROAD SPECTRUM LIGHT SOURCE/ CONTROLLER
10
12
30
34
32
20
22
24
38
8'
6'
1'
λn
λ1
F1
F1
F2
F2
IP
16
42
4'

FIG. 1B

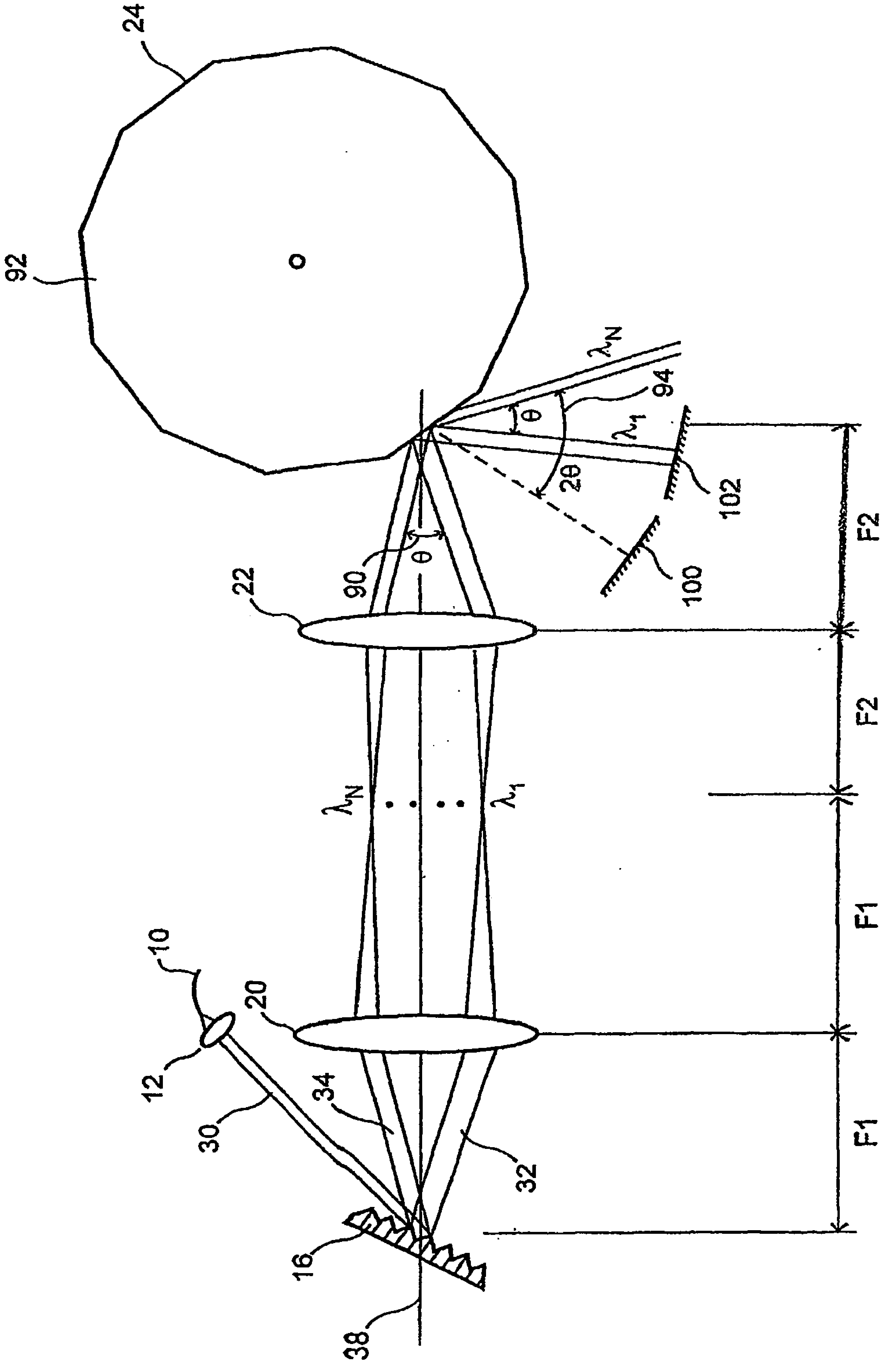

24
92
λ_N
94
θ
λ_1
2θ
102
100
F2
90
θ
22
λ_N
λ_1
F2
F1
10
20
12
30
34
32
F1
16
38

FIG. 1C

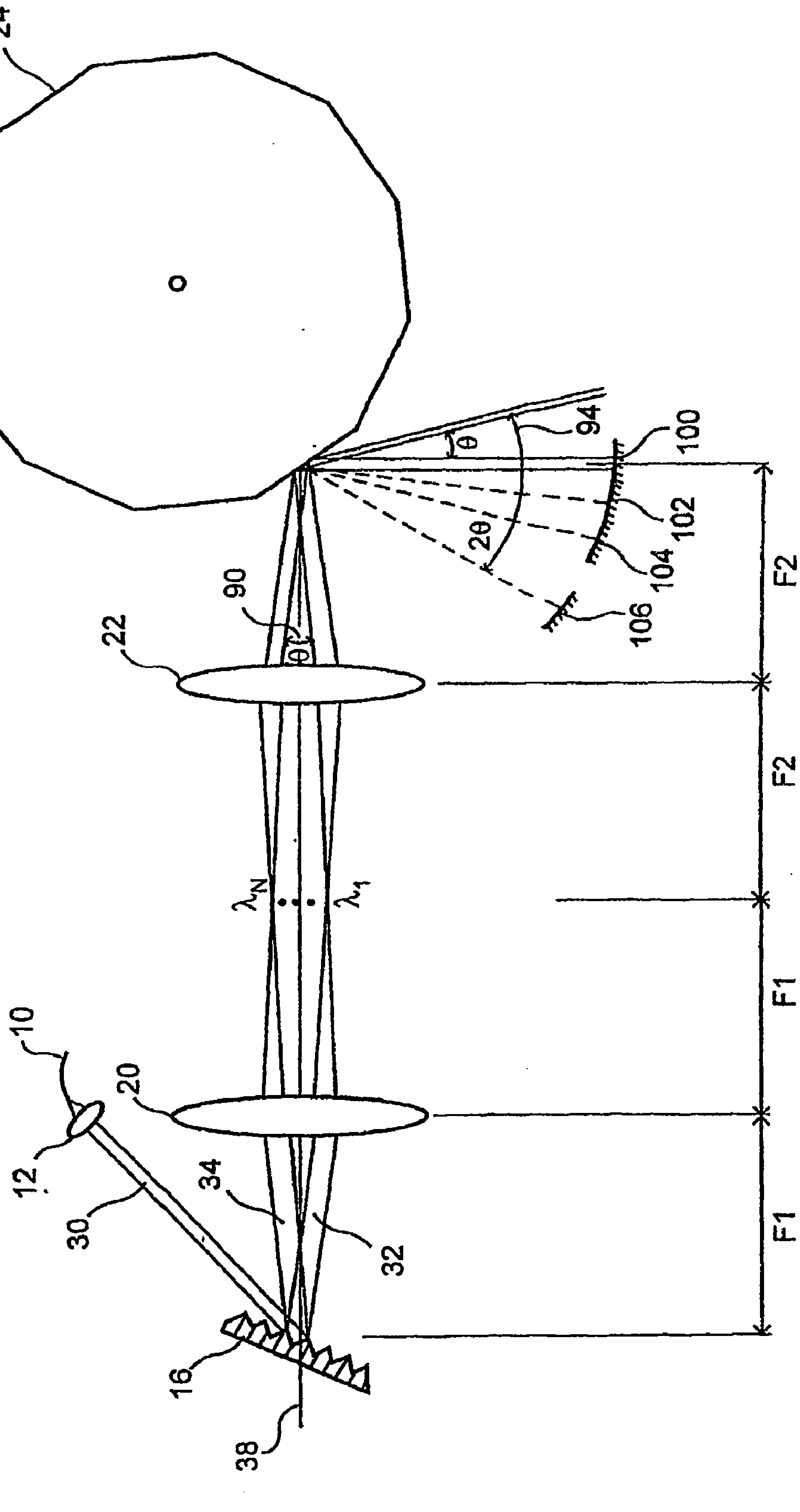
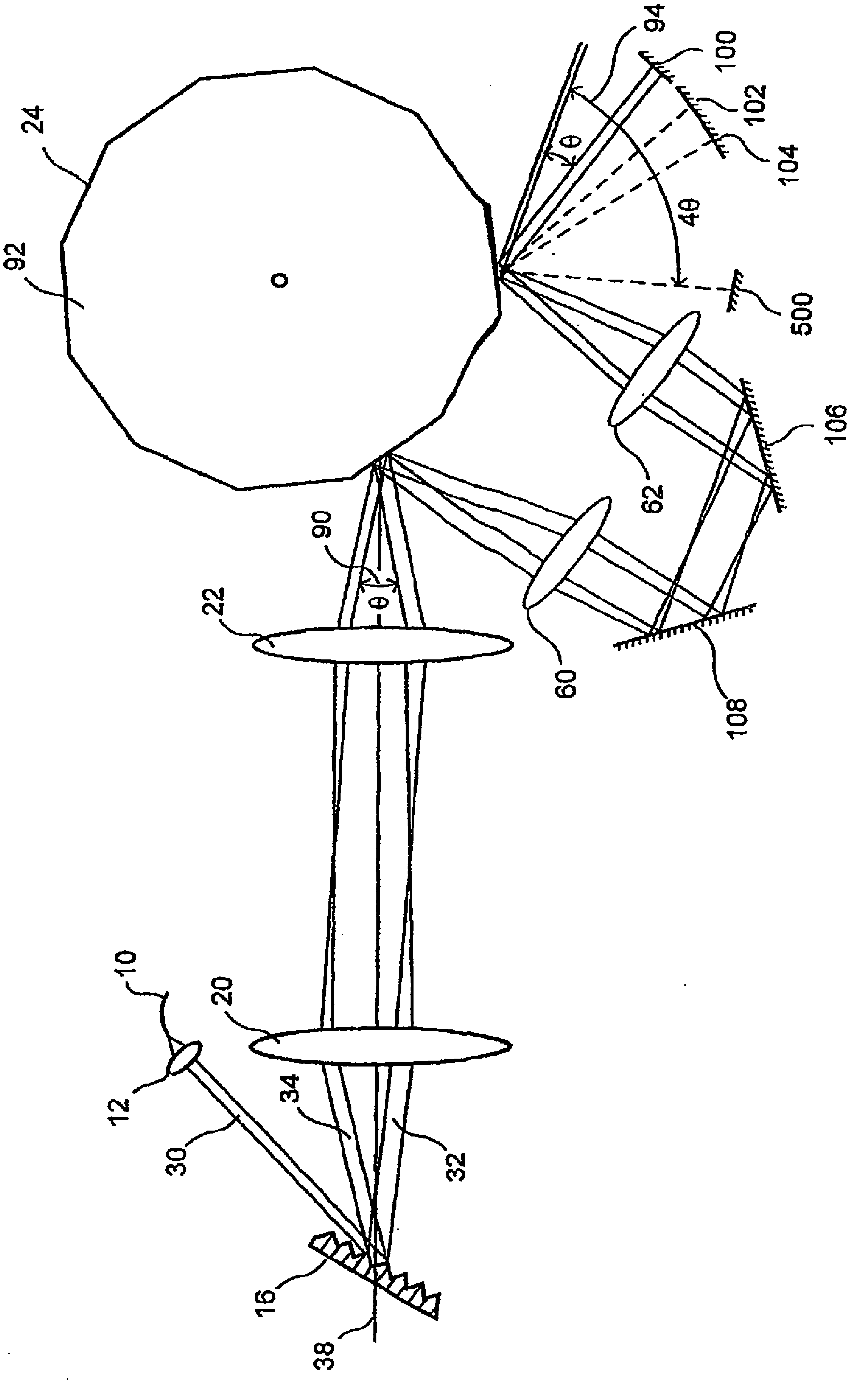

24
92
94
θ
100
102
2θ
104
106
90
θ
22
F2
F2
λ_N
λ_1
F1
F1
10
20
12
30
34
32
16
38

FIG. 1D


24
92
94
100
102
104
θ
4θ
500
106
62
108
60
22
90
θ
20
10
12
30
34
32
16
38

F I G. 1E

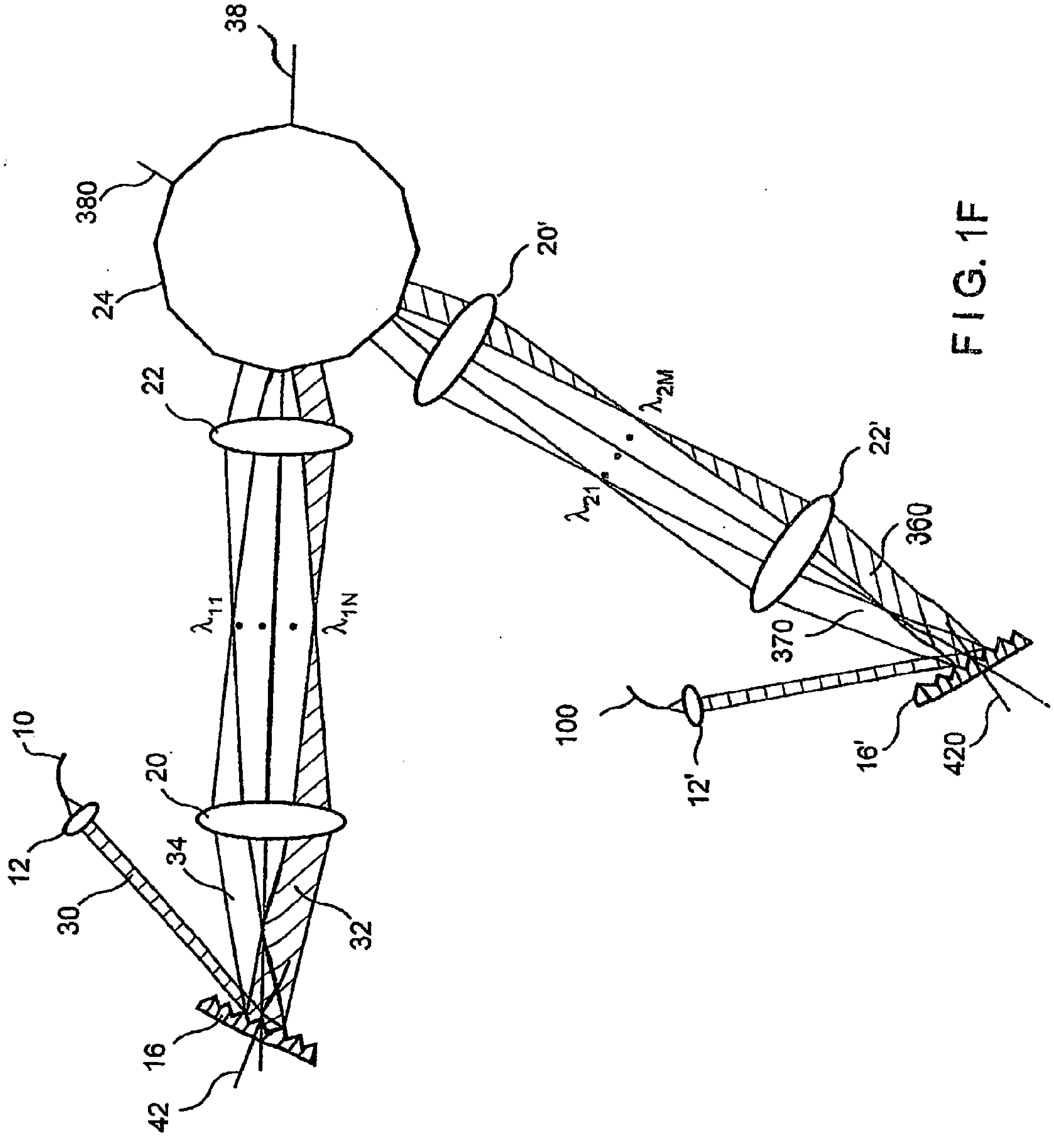

38
380
24
22
20'
λ_{2M}
λ_{21}
22'
360
370
λ_{11}
λ_{1N}
10
12
20
30
34
32
16
42
100
12'
16'
420

FIG. 1F

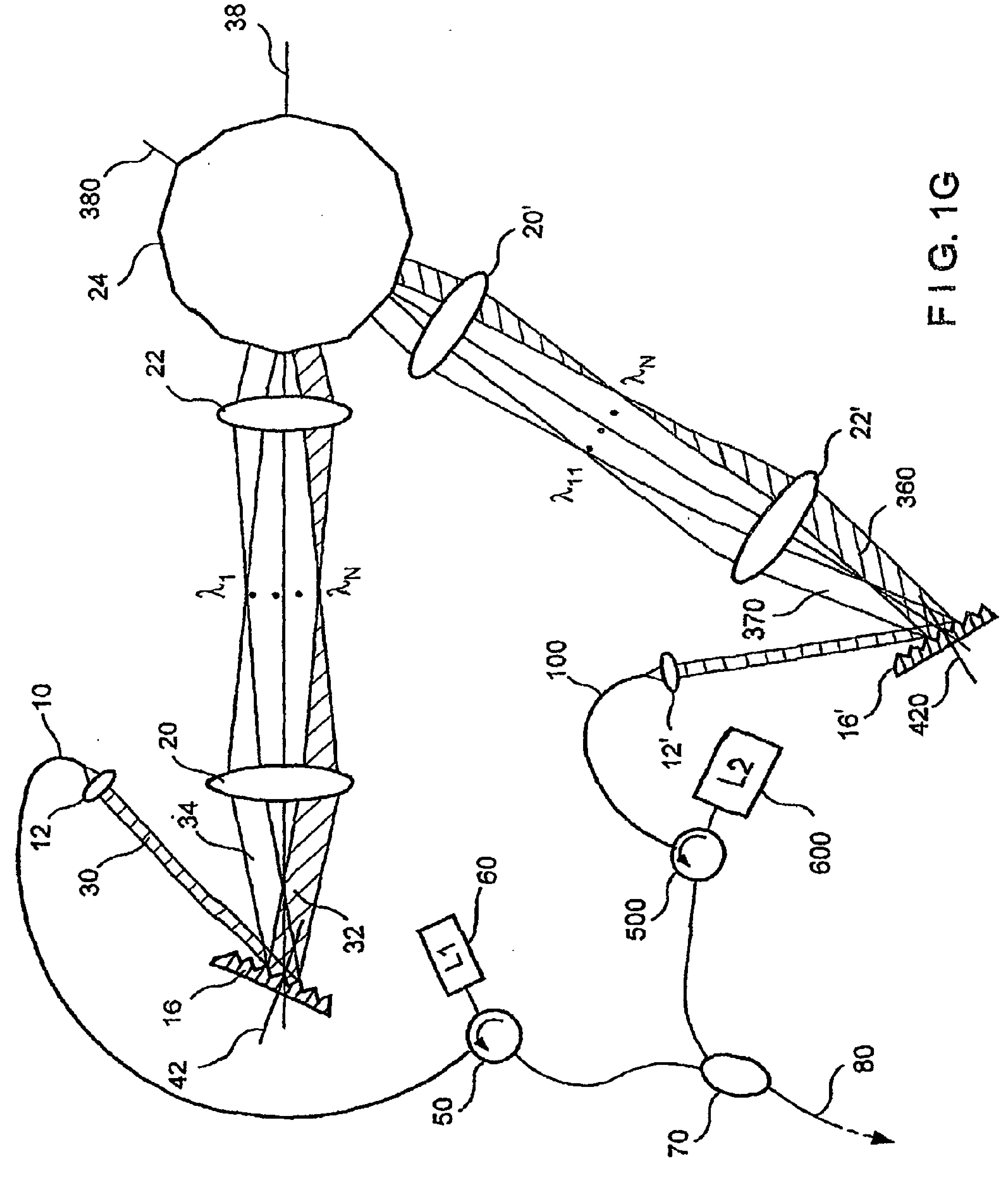
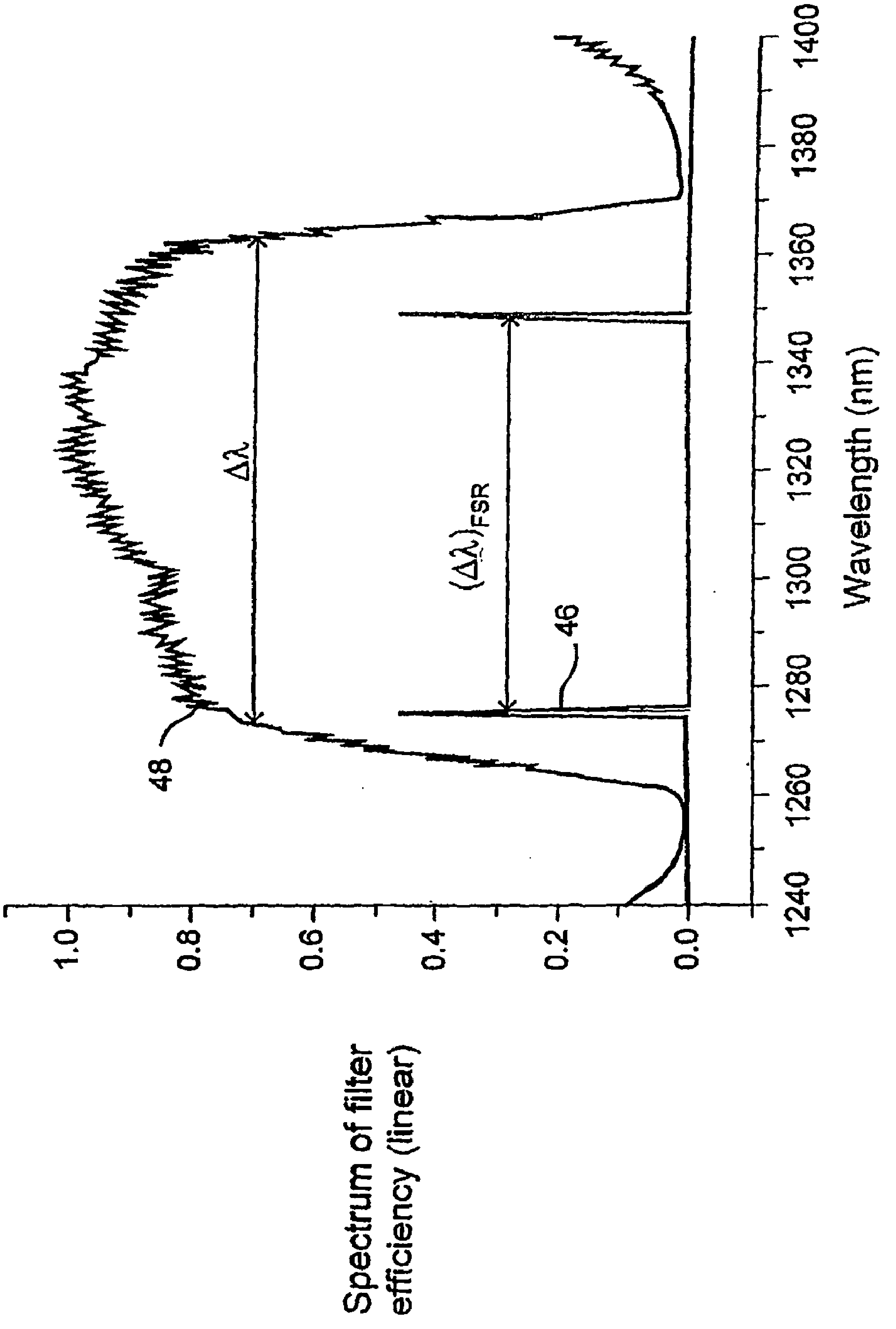

38
380
24
20'
22
λ_N
λ_{11}
22'
360
λ_1
λ_N
370
100
10
20
12
34
30
32
60
L1
16
42
50
12'
16'
420
L2
600
500
70
80

FIG. 1G



Spectrum of filter efficiency (linear)
1.0
0.8
0.6
0.4
0.2
0.0
1240
1260
1280
1300
1320
1340
1360
1380
1400
Wavelength (nm)
48
46
$\Delta\lambda$
$(\Delta\lambda)_{FSR}$

FIG. 2

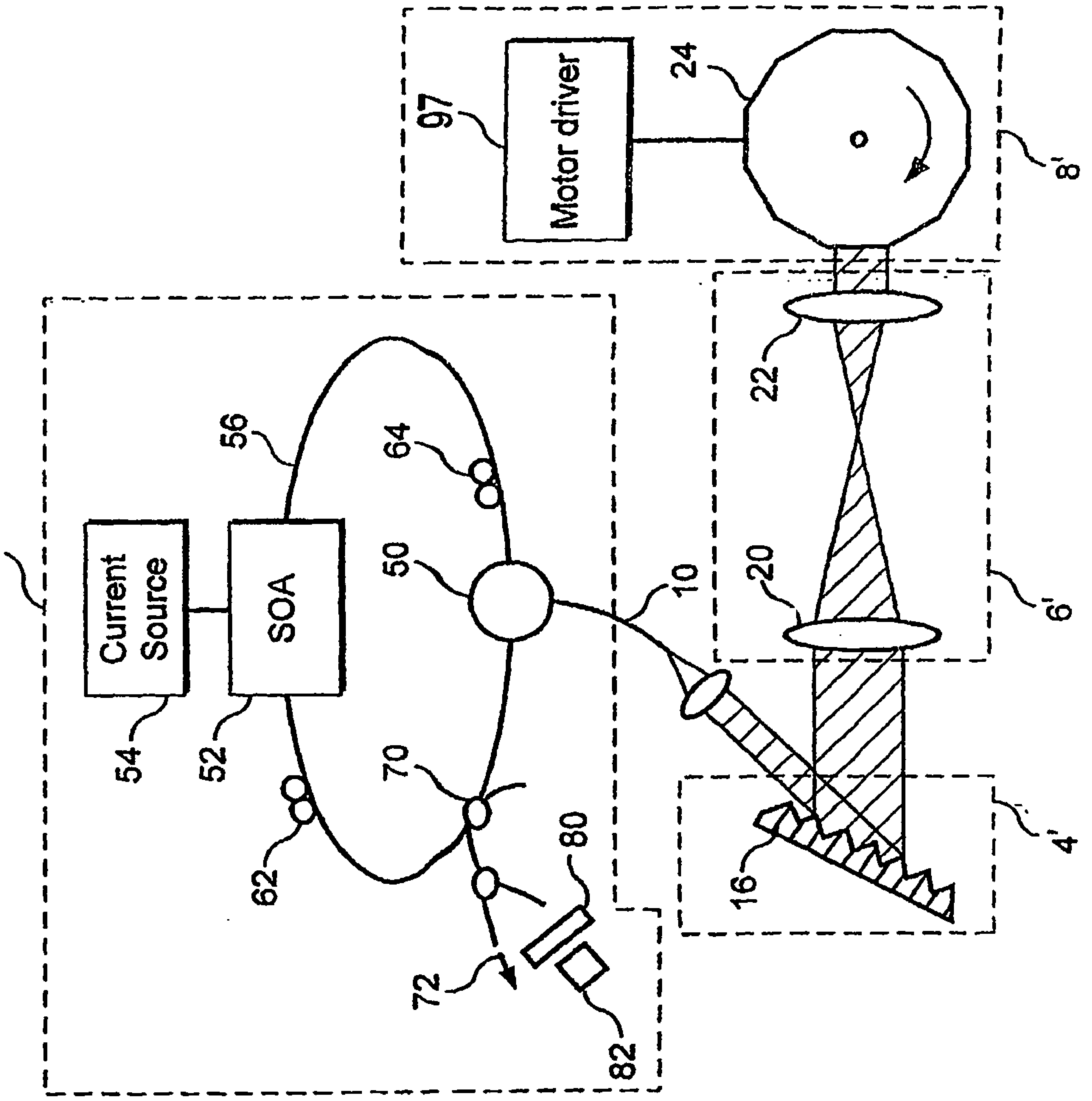
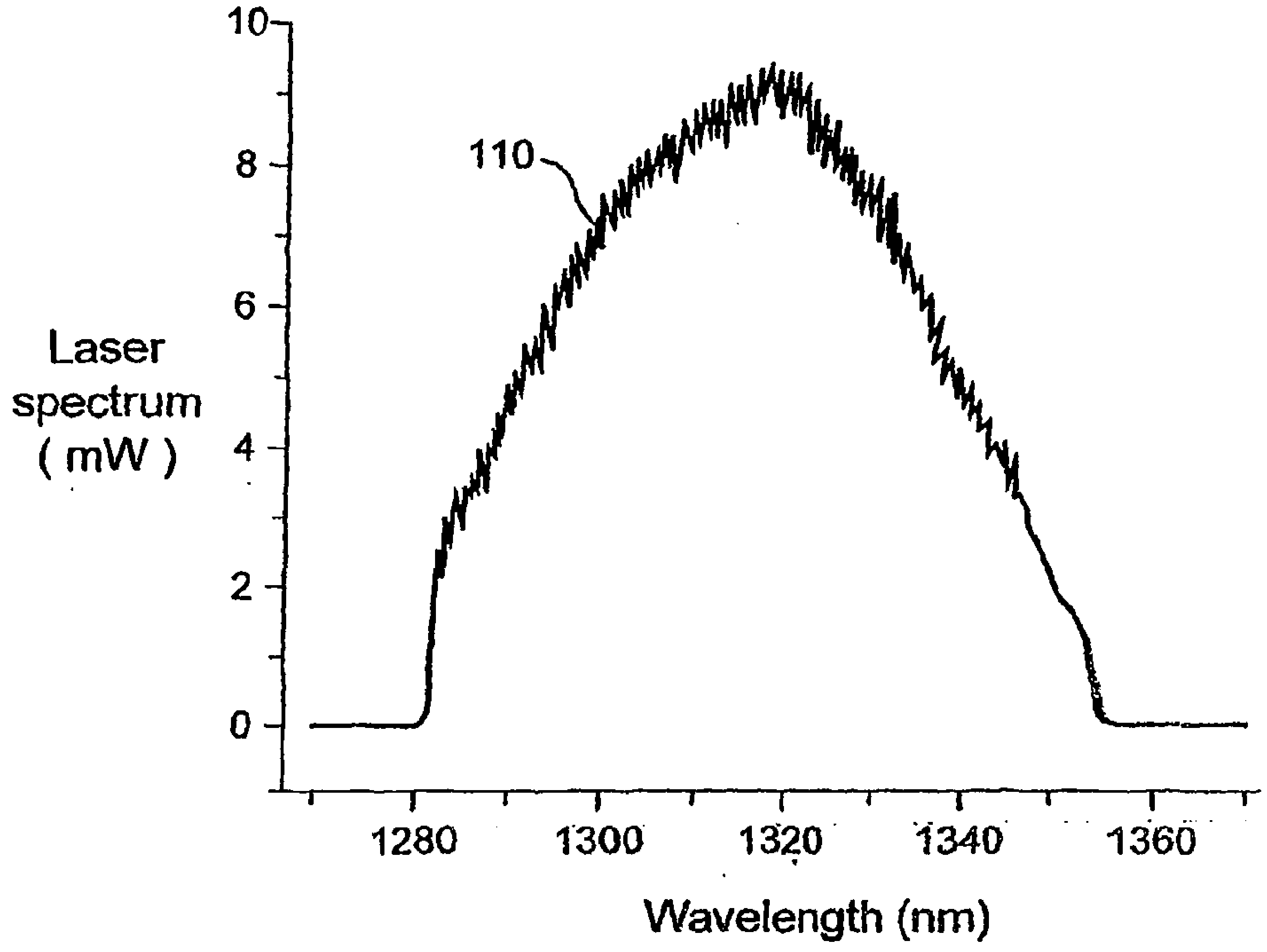
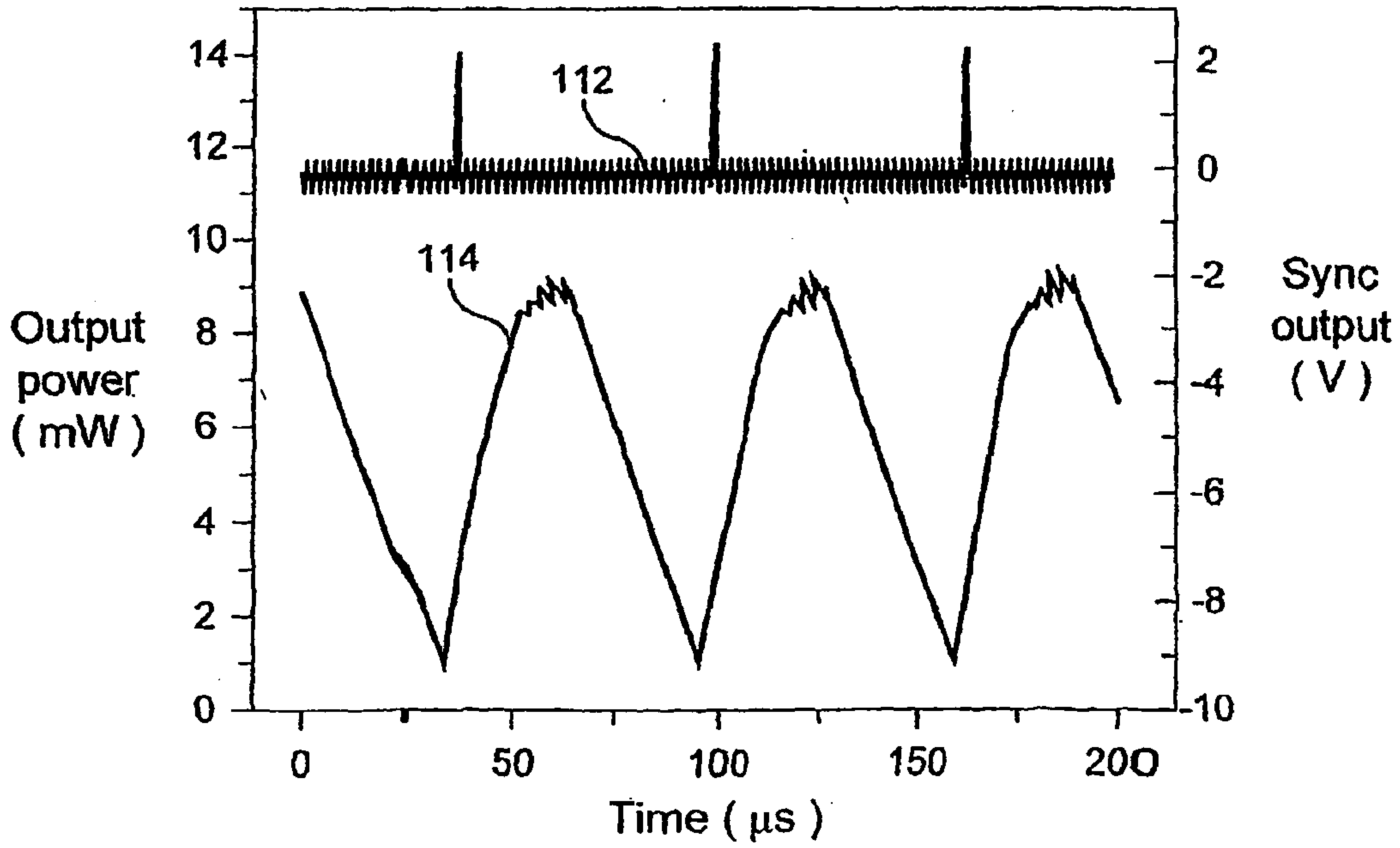

2'
Current Source
SOA
54
52
56
50
64
62
70
72
80
82
10
20
22
6'
16
4'
97
Motor driver
24
8'

FIG. 3


10
8
6
4
2
0
Laser spectrum (mW)
110
1280
1300
1320
1340
1360
Wavelength (nm)

F I G. 4A


14
12
10
8
6
4
2
0
Output power (mW)
112
114
2
0
-2
-4
-6
-8
-10
Sync output (V)
0
50
100
150
200
Time (µs)

F I G. 4B

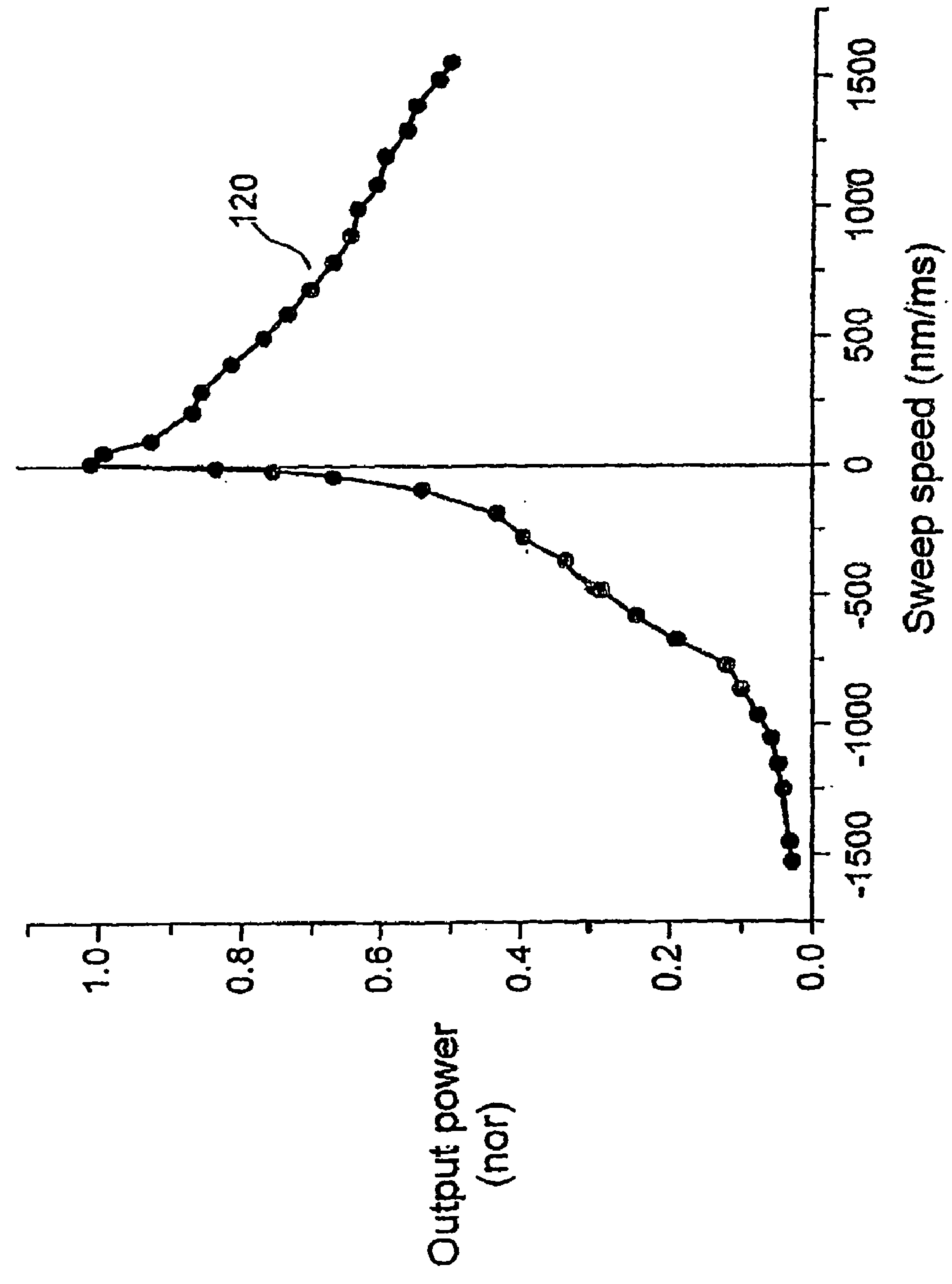

Output power
(nor)
1.0
0.8
0.6
0.4
0.2
0.0
-1500
-1000
-500
0
500
1000
1500
Sweep speed (nm/ms)
120

FIG. 5

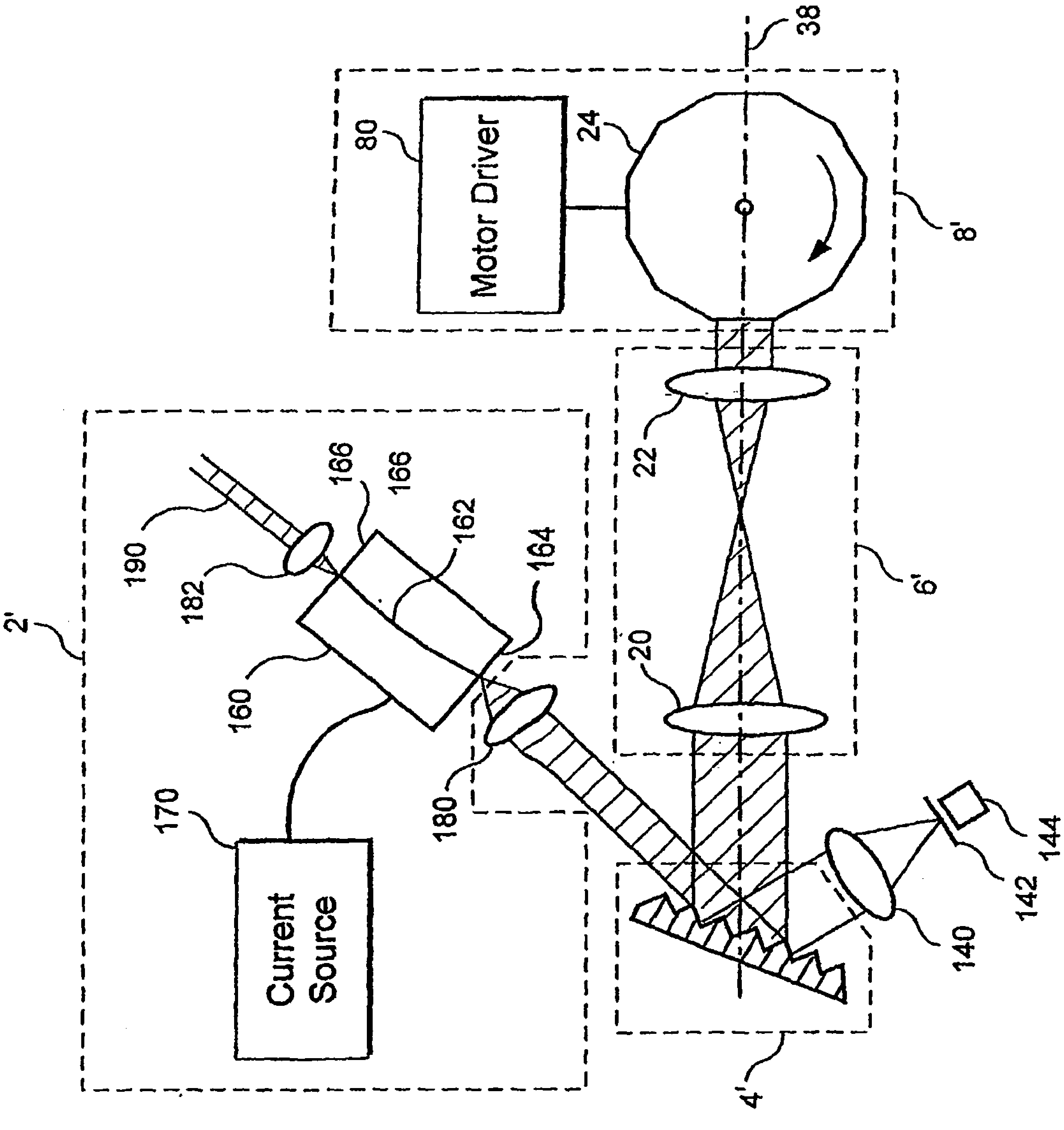

38
80
Motor Driver
24
8'
22
6'
20
166
166
162
164
190
182
160
2'
170
Current Source
180
140
142
144
4'

FIG.6

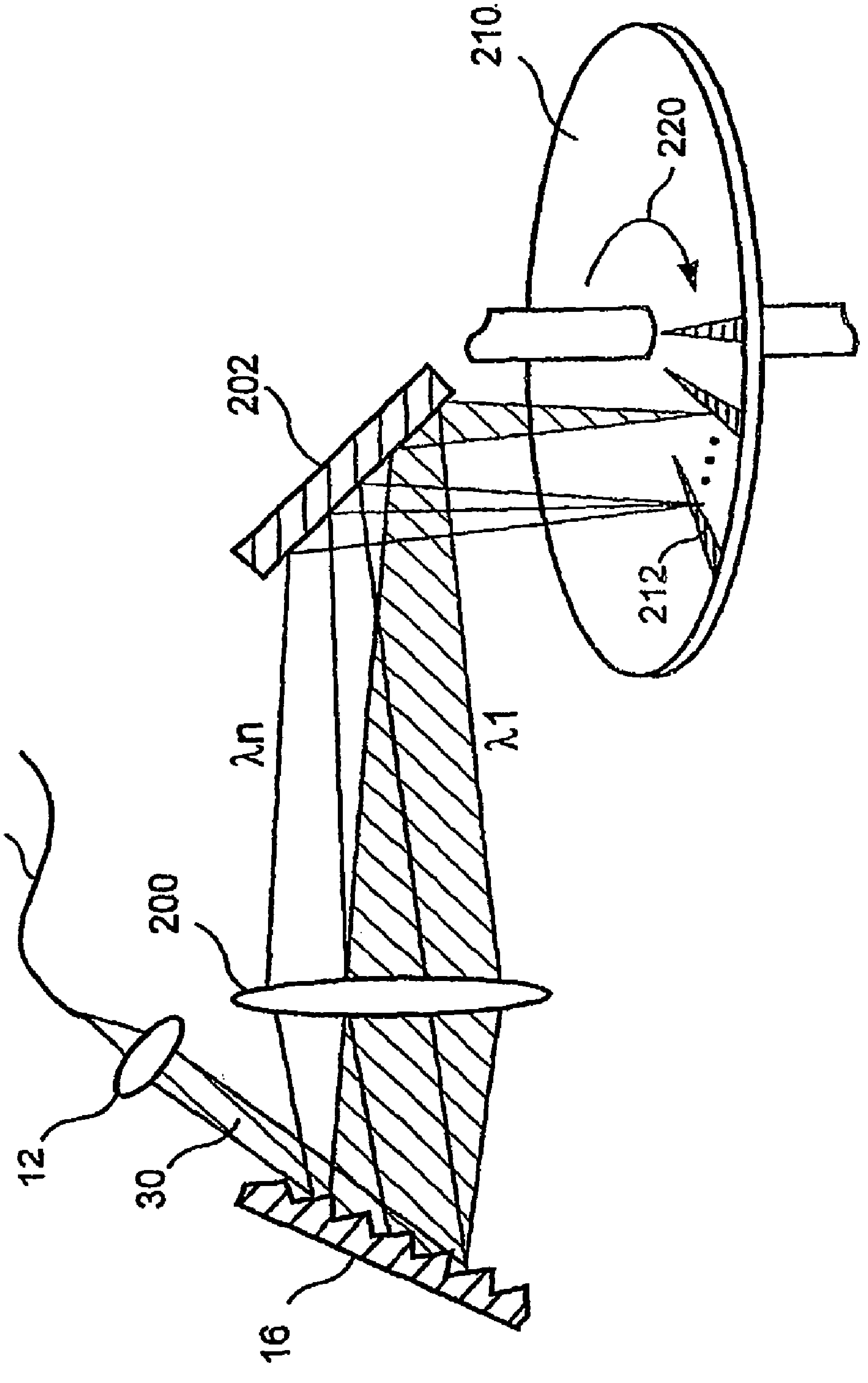
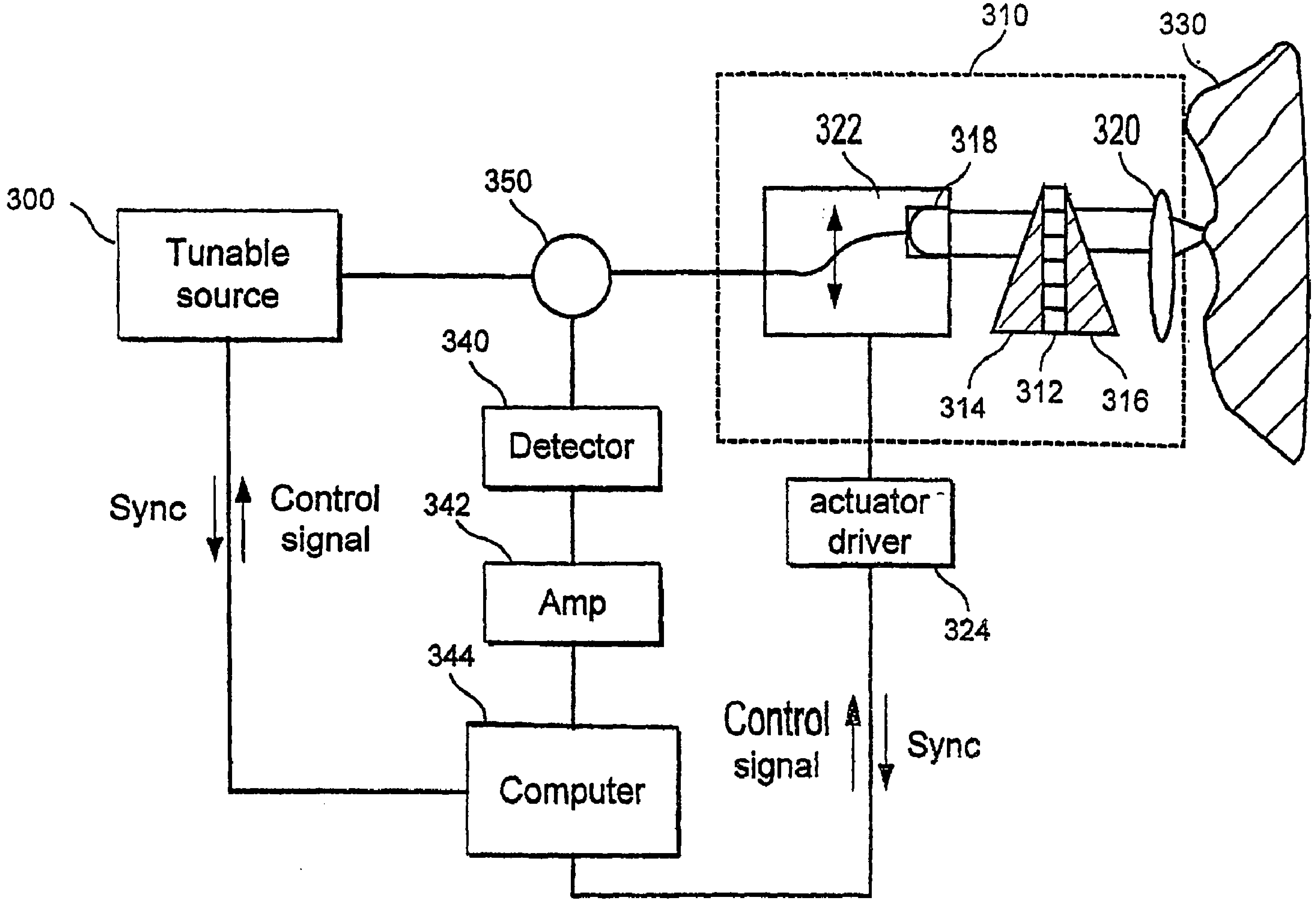


FIG. 7


300
Tunable source
350
310
330
322
318
320
314
312
316
340
Detector
342
Amp
344
Computer
actuator driver
324
Sync
Control signal
Control signal
Sync

F I G. 8

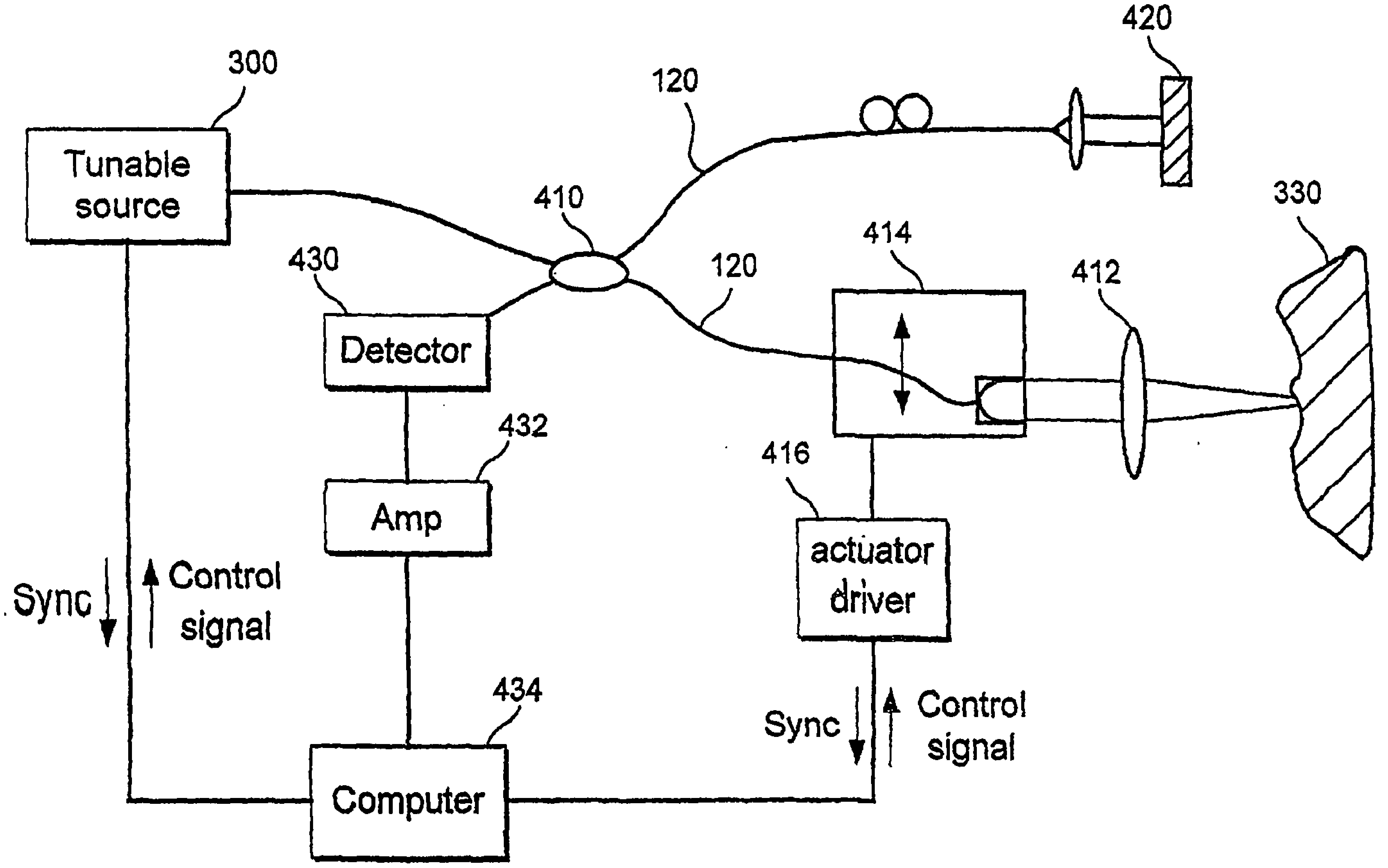
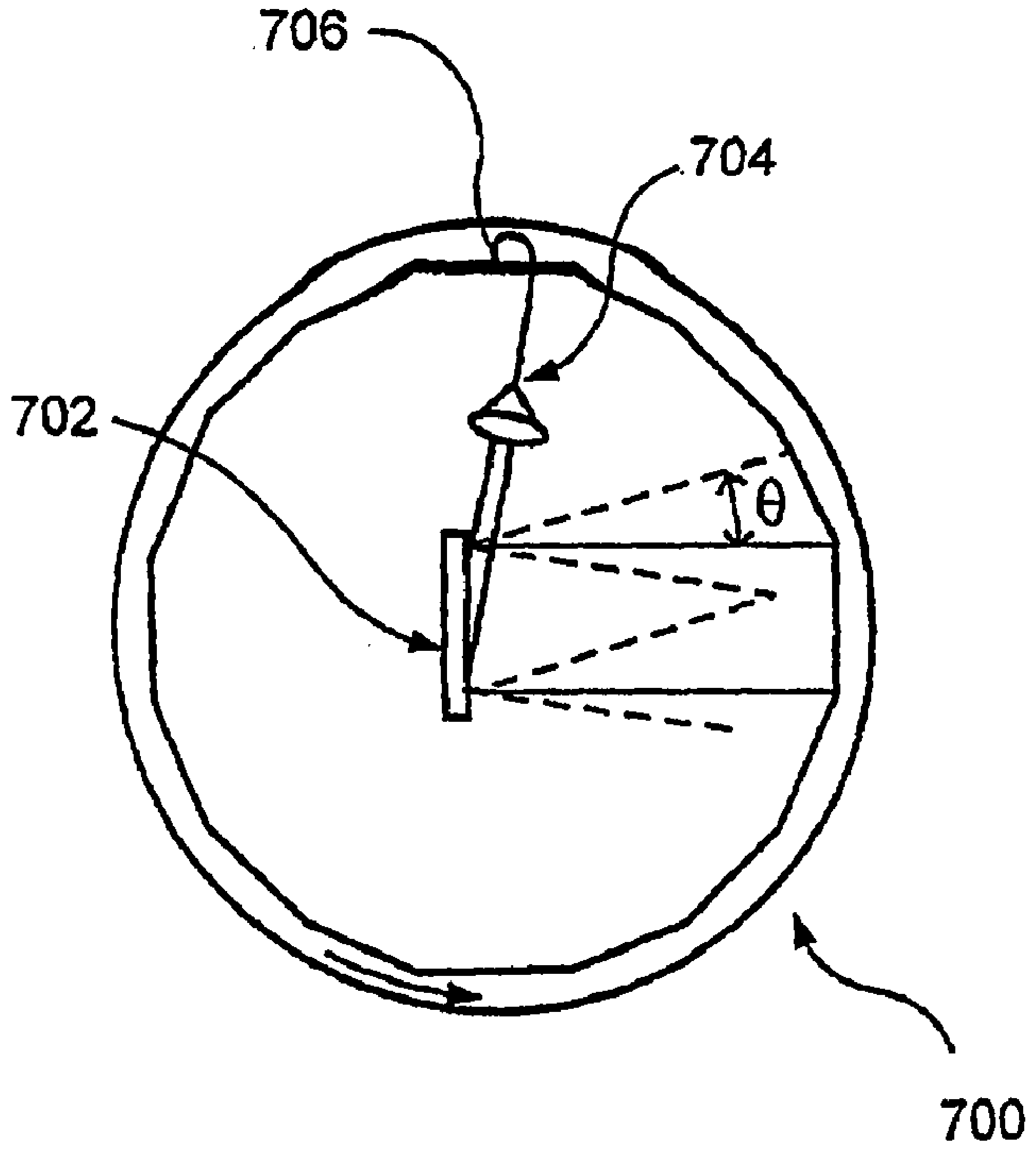
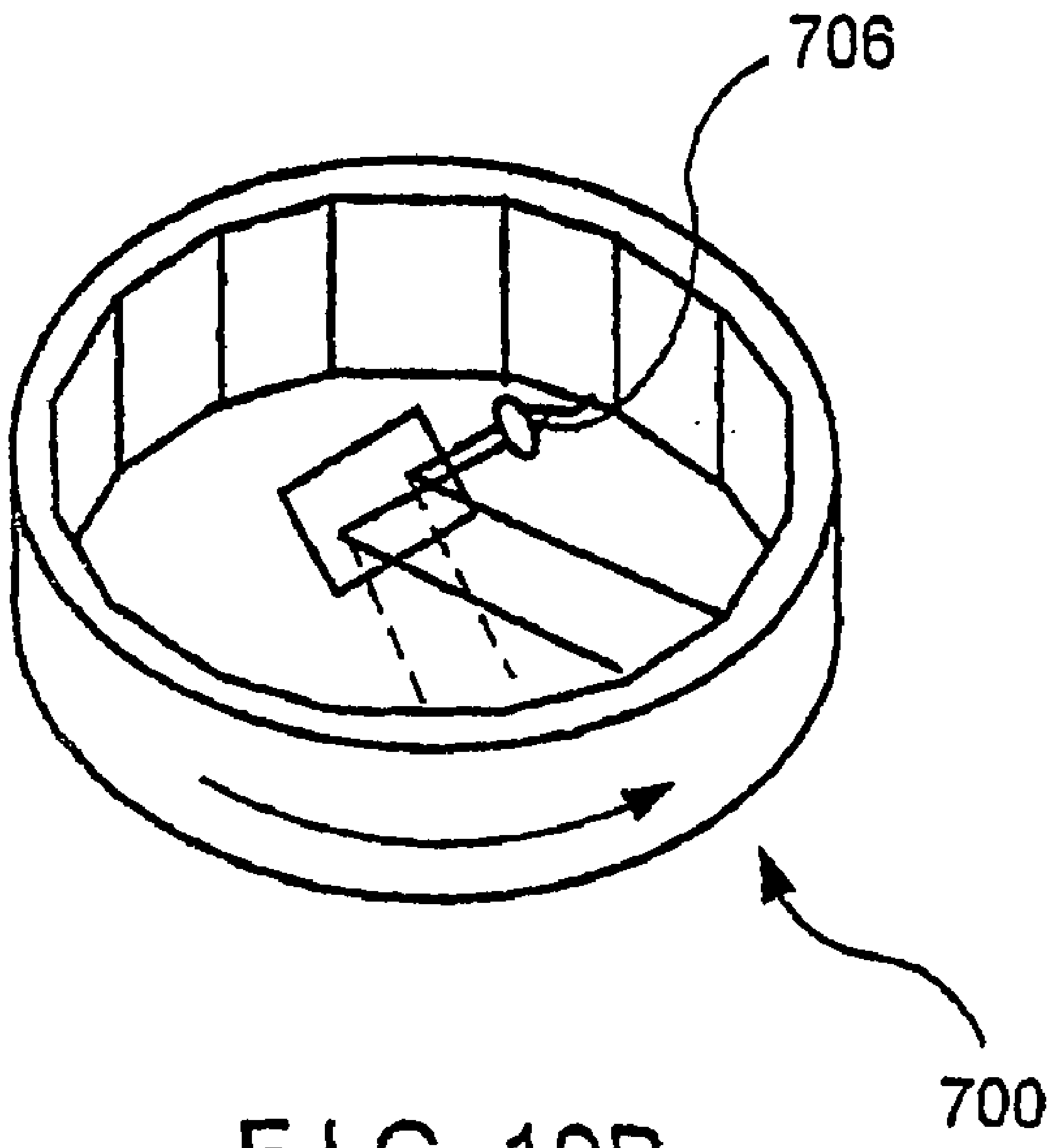

300
Tunable source
120
420
410
430
Detector
120
414
412
330
432
Amp
416
actuator driver
Sync
Control signal
434
Computer
Sync
Control signal

FIG. 9



F I G. 10A



F I G. 10B

PROCESS AND APPARATUS FOR A WAVELENGTH TUNING SOURCE

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a divisional of U.S. patent application Ser. No. 11/867,953 filed Apr. 11, 2008 now U.S. Pat. No. 7,724,786, which is a divisional of U.S. patent application Ser. No. 10/861,179 filed Jun. 4, 2004 now U.S. Pat. No. 7,519,096. This application also claims priority from U.S. Patent Application Ser. No. 60/476,600 filed on Jun. 6, 2003 and U.S. Patent Application Ser. No. 60/514,769 filed on Oct. 27, 2003, the entire disclosures of which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates generally to optical systems and more particularly to an optical wavelength filter system for wavelength tuning.

BACKGROUND OF THE INVENTION

Considerable effort has been devoted for developing rapidly and widely tunable wavelength laser sources for optical reflectometry, biomedical imaging, sensor interrogation, and tests and measurements. A narrow line width, wide-range and rapid tuning have been obtained by the use of an intra-cavity narrow band wavelength scanning filter. Mode-hopping-free, single-frequency operation has been demonstrated in an extended-cavity semiconductor laser by using a diffraction grating filter design. Obtaining single-frequency laser operation and ensuring mode-hop-free tuning, however, may use a complicated mechanical apparatus and limit the maximum tuning speed. One of the fastest tuning speeds demonstrated so far has been limited less than 100 nm/s. In certain applications such as biomedical imaging, multiple-longitudinal mode operation, corresponding to an instantaneous line width as large or great than 10 GHz, may be sufficient. Such width may provide a ranging depth of a few millimeters in tissues in optical coherence tomography and a micrometer-level transverse resolution in spectrally-encoded confocal microscopy.

A line width on the order of 10 GHz is readily achievable with the use of an intra-cavity tuning element (such as an acousto-optic filter, Fabry-Perot filter, and galvanometer-driven diffraction grating filter). However, the sweep frequency previously demonstrated has been less than 1 kHz limited by finite tuning speeds of the filters. Higher-speed tuning with a repetition rate greater than 15 kHz may be needed for video-rate (>30 frames/s), high-resolution optical imaging in biomedical applications.

Accordingly, there is a need to overcome the above-described deficiencies.

SUMMARY OF THE INVENTION

According to the exemplary concepts of the present invention, an optical wavelength filter may be provided that can be tuned with a repetition rate of greater than 15 kHz over a wide spectral range. In addition, a wavelength tuning source comprising such optical filter in combination with a laser gain medium may be provided. The tuning source may be useful in video-rate optical imaging applications, such as the optical coherence tomography and spectrally encoded confocal microscope.

In general, the optical filter according to one exemplary embodiment of the present invention may include a diffraction grating, a rotating polygon scanner, and a telescope. Such optical filter can be operated at a tuning speed more than an order of magnitude higher than the conventional filters. The wavelength tunable light source may be implemented by employing the filter, e.g., in combination with a laser gain medium. The filter and gain medium may further, be incorporated into a laser cavity. For example, a laser can emit a narrow band spectrum with its center wavelength being swept over a broad wavelength range at a high repetition rate.

In one exemplary embodiment of the present invention, an apparatus is provided which includes an arrangement for emitting an electromagnetic radiation that has a spectrum whose mean frequency changes substantially continuously over time. Such radiation is may be associated with a tuning speed that is greater than 100 terahertz per millisecond. The mean frequency can change repeatedly at a repetition rate that is greater than 5 kilohertz or over a range greater than 10 terahertz. The spectrum may have a tuning range covering a portion of the visible, near-infrared or infrared wavelengths. Exemplary spectra may be centered at approximately at 850 nm, 1300 nm or 1700 nm wavelengths. Further, the spectrum may have an instantaneous line width that is smaller than 100 gigahertz. The apparatus may also include a laser cavity with a roundtrip length shorter than 5 m. The apparatus may also have a polygon scanner arrangement which may be adapted to receive at least a portion of the emitted electromagnetic radiation and reflect or deflect the portion to a further location. In addition, a beam separating arrangement can be provided which selectively receives components of the electromagnetic radiation.

According to another exemplary embodiment of the present invention the apparatus for filtering an electromagnetic radiation can include at least one spectral separating arrangement configured to physically separate one or more components of the electromagnetic radiation based on a frequency of the electromagnetic radiation. The apparatus may also have at least one continuously rotating optical arrangement that is configured to receive the physically separated components and selectively direct individual components to a beam selecting arrangement.

In one exemplary variation of the present invention, the spectral separating arrangement includes a diffraction grating, a prism, a grism, an acousto-optic beam deflector, a virtual phased array, and/or an arrayed waveguide grating. The continuously rotating optical arrangement may be a polygon mirror, a diffractive element, a substantially opaque disk having an array of substantially transparent regions, and/or a substantially transparent disk having an array of substantially reflective regions. The spectral separating arrangement may also include a holographic grating mounted on a substrate comprising a continuously rotating optical arrangement.

In another exemplary variation of the present invention the beam selecting arrangement may be an optical fiber, an optical waveguide, a pinhole aperture, a combination of a lens with an optical fiber, waveguide or pinhole, and/or a spatial filter. The beam selecting arrangement can include a plurality of beam selecting elements, and the electromagnetic radiation which is transmitted by the plurality of beam selecting elements may be combined. The signal may be reflected multiple times from the continuously rotating optical arrangement before being received by the selecting arrangement.

According to yet another exemplary embodiment of the present invention the apparatus for filtering an electromagnetic radiation may include at least one spectral separating arrangement configured to angularly separate one or more components of the electromagnetic radiation based on a frequency of the electromagnetic radiation. Such arrangement can also include at least one angularly deflecting optical arrangement that includes a pivot point, and that is configured to receive the components of the electromagnetic radiation and selectively direct the components to a beam selecting arrangement. Further, the arrangement can include at least one optical imaging arrangement configured to receive the components of the electromagnetic radiation and generate an image of one or more dispersive elements associated with the components. The position of the pivot point of the angularly deflecting optical arrangement may be provided in proximity to a real or virtual image of at least one of the dispersive elements.

In one exemplary variant of the present invention, a deflection point of the angularly deflecting optical element may substantially overlap with a real image of at least one of the dispersive elements. At least one reflector which is configured to receive at least one signal from the at least one angularly deflecting optical arrangement may also be provided. One or more of the dispersive elements may be a diffraction grating, a prism, a grism, an acousto-optic beam deflector, a virtual phased array, and/or an arrayed waveguide grating. The angularly deflecting optical element may be a polygon mirror scanner, a galvanometer mirror scanner, or a piezo-electric mirror scanner.

According to still another exemplary embodiment of the present invention, an apparatus is provided for filtering an electromagnetic radiation. The apparatus includes at least one dispersive arrangement configured to angularly separate components of the electromagnetic radiation based on a frequency of the electromagnetic radiation, and generate frequency-separated components. The apparatus may also include at least one angularly deflecting optical element having a pivot point of an angular deflection. The pivot point can substantially overlap a location where substantially all of the frequency-separated components overlap.

In another exemplary embodiment of the present invention, at least one spectral separating arrangement can be provided that is configured to physically separate one or more components of the electromagnetic radiation based on a frequency of the electromagnetic radiation. In addition, at least one continuously rotating optical arrangement may be included which is configured to receive at least one signal that is associated with the one or more components. At least one beam selecting arrangement may also be configured to receive the signal. The emitter can be a laser gain medium, a semiconductor optical amplifier, a laser diode, a super-luminescent diode, a doped optical fiber, a doped laser crystal, a doped laser glass, and/or a laser dye.

In still another exemplary embodiment of the present invention, a source arrangement can provide an electromagnetic radiation. The source includes at least one emitter of the electromagnetic radiation, at least one spectral separating arrangement configured to angularly separate one or more components of the electromagnetic radiation based on a frequency of the electromagnetic radiation, as well as at least one angularly deflecting optical arrangement that includes a pivot point, and configured to receive the components of the electromagnetic radiation to generate at least one signal associated with the one or more components. In addition, the source arrangement can include at least one beam selecting arrangement adapted to receive the signal, and selectively generate at least one selected signal, and at least one optical imaging arrangement configured to received the selected signal, and generate an image of one or more dispersive elements associated with the one or more components. In a variation of the present invention, more than one laser gain medium providing electromagnetic radiation and at least one spectral separating arrangement configured to physically separate one or more components of the electromagnetic radiation based on a frequency of the electromagnetic radiation can be provided. In this variation, the selected components of electromagnetic radiation from each laser gain medium are synchronized, and can be used separately or combined.

In one further exemplary embodiment of the present invention, a high-speed tuning of an extended-cavity semiconductor laser may be provided. The laser resonator may include a unidirectional fiber-optic ring, a semiconductor optical amplifier as the gain medium, and a scanning filter based on a polygon scanner. Variable tuning rates of up to 1,150 nm/ms (15.7 kHz repetition frequency) can be obtained over a 70 nm wavelength span centered at 1.32 μm. Such tuning rate can be more than an order of magnitude faster than is conventionally know, and may be facilitated in part by self-frequency shifting in the semiconductor optical amplifier. The instantaneous line width of the source may be <0.1 nm for 9-mW cw output power, and a low spontaneous-emission background of 80 dB can be obtained.

Other features and advantages of the present invention will become apparent upon reading the following detailed description of embodiments of the invention, when taken in conjunction with the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Further objects, features and advantages of the invention will become apparent from the following detailed description taken in conjunction with the accompanying figures showing illustrative embodiments of the invention, in which:

FIG. **1**A is a block diagram of a first exemplary embodiment of an optical wavelength filter according to the present invention;

FIG. **1**B is a block diagram of a second exemplary embodiment of the optical wavelength filter according to the present invention;

FIG. **1**C is a block diagram of a third exemplary embodiment of the optical wavelength filter according to the present invention;

FIG. **1**D is a block diagram of a fourth exemplary embodiment of the optical wavelength filter according to the present invention;

FIG. **1**E is a block diagram of a fifth exemplary embodiment of the optical wavelength filter according to the present invention;

FIG. **1**F is a block diagram of a sixth exemplary embodiment of the optical wavelength filter according to the present invention;

FIG. **1**G is a block diagram of a seventh exemplary embodiment of the optical wavelength filter according to the present invention;

FIG. **2** is a graph of exemplary characteristics of the optical wavelength filter according to the present invention;

FIG. **3** is an exemplary embodiment of the wavelength tuning laser source according to the present invention;

FIG. **4**A is a graph of exemplary first output characteristics (laser spectrum vs. wavelength) of the laser source according to the present invention;

FIG. **4**B is a graph of exemplary second output characteristics (output power vs. time) of the laser source according to the present invention;

FIG. **5** is a graph of exemplary output power provided as a function of sweep speed according to the present invention;

FIG. **6** is an exemplary embodiment of a free-space extended-cavity semiconductor tunable laser arrangement according to the present invention;

FIG. **7** is an illustration of a seventh exemplary embodiment of the optical wavelength filter according to the present invention;

FIG. **8** is a schematic diagram of an exemplary embodiment of a spectrally-encoded confocal microscope that utilizes the tunable laser source according to the present invention;

FIG. **9** is a schematic diagram of an exemplary embodiment of a frequency-domain optical coherence tomography arrangement that utilizes the tunable laser source according to the present invention;

FIG. **10**A is a top view of an eighth exemplary embodiment of the wavelength filter according to the present invention; and

FIG. **10**B is a perspective plan view of the wavelength filter shown in FIG. **10**A.

DETAILED DESCRIPTION

FIG. **1**A shows a block diagram of a first exemplary embodiment of an optical wavelength filter **1** in accordance the present invention. In this first exemplary embodiment, the optical wavelength filter **1** can be used in a variety of different applications, general examples of which are described below. In this example, the filter **1** may be coupled to one or more applications **3** via a light source **2**. It should be understood that in certain exemplary applications, the filter **1** can be used with or connected to an application (e.g., one or more of the applications **3**) via a device other than a light source (e.g. a passive or active optical element). In the first exemplary embodiment shown in FIG. **1**A, a broad spectrum light source and/or controller **2** (hereinafter referred to as "light controller"), may be coupled to a wavelength dispersing element **4**. The light controller **2** can be further coupled to one or more of the applications **3** that are adapted to perform one or more tasks with or for, including but not limited to, optical imaging processes and optical imaging systems, laser machining processes and systems, photolithography and photolithographic systems, laser topography systems, telecommunications processes and systems, etc. The wavelength dispersing element **4** can be coupled to a lens system **6**, which is further coupled to a beam deflection device **8**.

The light controller **2** can be one or more of various systems and/or arrangements that are configured to transmit a beam of light having a broad frequency (f) spectrum. In one exemplary embodiment, the beam of light may be a collimated beam of light The beam of light can include a plurality of wavelengths λ . . . λn, within the visible light spectrum (e.g., red, blue, green). Similarly, the beam of light provided by the light controller **2** can also include a plurality of wavelengths λ . . . λn that may be defined outside of the visible spectrum (e.g., ultraviolet, near infrared or infrared). In one exemplary embodiment of the present invention, the light controller **2** can include a unidirectional light transmission ring, which shall be described in further detail below in connection with FIG. **3** which shows an exemplary embodiment of a wavelength tuning laser source. Further, in another exemplary embodiment of the present invention, the light controller **2** can include a linear resonator system, which shall be described in further detail below in connection with FIG. **6**.

The wavelength dispersing element **4** of the optical wavelength filter **1** can include one or more elements that are specifically adapted to receive the beam of light from the light controller **2**, and to conventionally separate the beam of light into a plurality of wavelengths of light having a number of directions. The wavelength dispersing element **4** is further operative to direct portions of light having different wavelengths in equal angular directions or displacements with respect to an optical axis **38**. In one exemplary embodiment of the present invention, the wavelength dispersing element **4** can include a light dispersion element, which may include but not limited to, a reflection grating, a transmission grating, a prism, a diffraction grating, an acousto-optic diffraction cell or combinations of one or more of these elements.

The lens system **6** of the optical wavelength filter **1** can include one or more optical elements adapted to receive the separated wavelengths of light from the wavelength dispersing element. Light at each wavelength propagates along a path which is at an angle with respect to the optical axis **38**. The angle is determined by the wavelength dispersing element **4**. Furthermore, the lens system **6** is adapted to direct or steer and/or focus the wavelengths of light to a predetermined position located on a beam deflection device **8**.

The beam deflection device **8** can be controlled to receive and selectively redirect one or more discrete wavelengths of light back along the optical axis **38** through the lens system **6** to the wavelength dispersing element **4** and back to the light controller **2**. Thereafter, the light controller **2** can selectively direct the received discrete wavelengths of light to any one or more of the applications. The beam deflecting device **8** can be provided in many different ways. For example, the beam deflecting device **8** can be provided from elements including, but not limited to, a polygonal mirror, a planar mirror disposed on a rotating shaft, a mirror disposed on a galvanometer, or an acousto-optic modulator.

FIG. **1**B shows a schematic diagram of a second exemplary embodiment of the optical wavelength filter **1'**. The exemplary optical wavelength filter **1'** can be configured as a reflection-type filter which may have substantially identical input and output ports. An input/output optical fiber **10** and a collimating lens **12** can provide an input from a light controller **2'** (which may be substantially similar to the light controller **2** described above with reference to FIG. **1**A) to the optical wavelength filter **1'**. The optical wavelength filter **1'** includes a diffraction grating **16**, optical telescoping elements **6'** (hereinafter referred to as "telescope **6'**" and may possibly be similar to the lens system **6** of FIG. **1**A), and a polygon mirror scanner **24**. The telescope **6'** can include two lenses, e.g., first and second lenses **20**, **22** with 4-f configuration.

In the second exemplary embodiment of the optical wavelength filter **1'** shown in FIG. **1**B, the telescope **6'** includes the first and second lenses **20**, **22**, which are each substantially centered along the optical axis **38**. The first lens **20** may be located at a first distance from the wavelength dispensing element **4'** (e.g., diffraction grating **16**), which can approximately be equal to the focal length F**1** of the first lens **20**. The second lens **22** may be located at a second distance from the first lens **20**, which can be approximately equal to the sum of the focal length F**1** of the first lens **20** and the focal length F**2** of the second lens **22**. Using such arrangement, the first lens **20** can receive one or more collimated discrete wavelengths of light from the wavelength dispersing element **4'**, and can effectively perform a Fourier Transform on each one of the collimated one or more discrete wavelengths of light to provide one or more approximately equal converging beams that are projected onto an image plane IP.

The image plane IP is preferably located between the first lens **20** and the second lens **22** and at a predetermined distance from the first lens **20**. According to one exemplary variation of the present invention, such predetermined distance may be defined by the focal length F**1** of the first lens **20**. After such one or more converging beams are propagated through the image plane IP, these one or more converging beams form equal or corresponding one or more diverging beams that are received by the second lens **22**. The second lens **22** is adapted to receive the diverging beams and provide approximately an equal number of collimated beams having predetermined angular displacements with respect to the optical axis **38**. Thus, the second lens **22** can direct or steer the collimated beams to predefined portions of the beam deflection device **8'**.

The telescope **6'** according to the second exemplary embodiment of the present invention is operative to provide one or more features as described above, as well as to convert a diverging angular dispersion from the grating into converging angular dispersion after the second lens **22**. Such result may be advantageous for a proper operation of the filter. In addition, the telescope **6'** may provide adjustable parameters which control the tuning range and linewidth and reduce the beam size at the polygon mirror to avoid beam clipping. As is illustrated in the exemplary embodiment of FIG. **1**B, a beam deflection device **6'** (e.g., which may include a polygon mirror or arrangement **24**) is adapted to preferably reflect back only the spectral component within a narrow passband as a function of the angle of the front mirror facet of the polygon arrangement **24** with respect to the optic axis **38**. The reflected narrow band light is diffracted and received by the optical fiber **10**. The orientation of the incident beam **30** with respect to the optic axis and a rotation direction **40** of the polygon arrangement **24** can be used to determine the direction of wavelength tuning, e.g., a wavelength up (positive) scan or a wavelength down (negative) scan. The exemplary arrangement shown in FIG. **1**B can generate a positive wavelength sweep. It should be understood that although the polygon arrangement **24** is shown in FIG. **1**B as having twelve facets, polygon arrangements which have fewer than twelve facets or greater than twelve facets can also be used. While generally not considering practical mechanical limits, based upon conventional manufacturing techniques, a particular number of facets of the polygon arrangement **24** to use in any application may depend on a desired scanning rate and a scanning range for a particular application.

Furthermore, the size of the polygon arrangement **24** may be selected based on preferences of a particular application, and preferably taking into account certain factors including, but not limited to, manufacturability and weight of the polygon arrangement **24**. It should also be understood that lenses **20**, **22** that have different focal lengths may be provided. For example, the lenses **20**, **22** should be selected to provide a focal point at approximately the center point **24***a* of the polygon arrangement **24**.

In one exemplary embodiment, a Gaussian beam **30** can be utilized with a broad optical spectrum incident to the grating from the fiber collimator **12**. The well-known grating equation is expressed as $\lambda=p\cdot(\sin\alpha+\sin\beta)$ where λ is the optical wavelength, p is the grating pitch, and α and β are the incident and diffracted angles of the beam with respect to the normal axis **42** of the grating, respectively. The center wavelength of tuning range of the filter may be defined by $\lambda_0=p\cdot(\sin\alpha+\sin\beta_0)$ where β_0 is the angle between the optic axis **38** of the telescope and the grating normal axis. FWHM bandwidth of the filter is defined by $(\delta\lambda)_{FWHM}/\lambda_0=A\cdot(p/m)\cos\alpha/W$, where $A=\sqrt{4\ln 2}/\pi$ for double pass, m is the diffraction order, and W is $1/e^2$-width of the Gaussian beam at the fiber collimator.

Tuning range of the filter may be limited by the finite numerical aperture of the first lens **20**. The acceptance angle of the first lens **20** without beam clipping may be defined by $\Delta\beta=(D_1-W\cos\beta_0/\cos\alpha)/F_1$, where D_1 and F_1 are the diameter and focal length of the first lens **20**. Such formulation relates to the filter tuning range via $\Delta\lambda=p\cos\beta_0\cdot\Delta\beta$. One of exemplary design parameters of the filter, originated from the multiple facet nature of the polygon mirror, is the free spectral range, which is described in the following. A spectral component after propagating through the first lens **20** and the second lens **22** may have a beam propagation axis at an angle β' with respect to the optic axis **38**, e.g., $\beta'=-(\beta-\beta_0)\cdot(F_1/F_2)$, where F_1 and F_2 are the focal lengths of the first lens **20** and the second lens **22**, respectively. The polygon arrangement **24** may have a facet-to-facet polar angle given by $\theta=2\pi/N\approx L/R$, where L is the facet width, R is the radius of the polygon and N is the number of facets. If the range of β' of incident spectrum is greater than the facet angle, i.e. $\Delta\beta'=\Delta\beta\cdot(F_1/F_2)>\theta$, the polygon arrangement **24** can retro-reflect more than one spectral component at a given time. The spacing of the multiple spectral components simultaneously reflected, or the free spectral range, can be defined as $(\Delta\lambda)_{FSR}=p\cos\beta_0(F_1/F_2)\cdot\theta$. In an exemplary intra-cavity scanning filter application, the free spectral range of the filter should exceed the spectral range of the gain medium in order to avoid multiple frequency bands (in the case of an inhomogeneously broadened gain medium) or limited tuning range (in the case of a homogeneously broadened gain medium).

The duty cycle of laser tuning by the filter can be, for example, 100% with no excess loss caused by beam clipping if two preferable conditions are met as follows:

$$W<\frac{\cos\alpha F_1}{\cos\beta F_2}L \text{ and } W<\frac{\cos\alpha}{\cos\beta_0}(F_2-S)\cdot\theta \tag{1}$$

The first equation may be derived from a condition that the beam width after the second lens **22** should be smaller than the facet width. The second equation can be derived from that the two beams at the lowest **32** and highest wavelengths **34** of the tuning range, respectively, which should not overlap each other at the polygon arrangement **24**. S in equation (1) denotes the distance between the second lens **22** and the front mirror of the polygon arrangement **24**.

It is possible to select the optical components with the following parameters: W=2.4 mm, p=1/1200 mm, α=1.2 rad, β_0=0.71 rad, m=1, $D_1=D_2$=25 mm, F_1=100 mm, F_2=45 mm, N=24, R=25 mm, L=6.54, S=5 mm, θ=0.26 rad, λ_0=1320 nm. From the parameters, the theoretical FWHM bandwidth, tuning range and free spectral range of the filter could be calculated: $(\delta\lambda)_{FWHM}$=0.09 nm, $\Delta\lambda$=126 nm and $(\Delta\lambda)_{FSR}$=74 nm. Both conditions in equation (1) may be satisfied with particular margins.

FIG. **1**C shows a diagram of a third exemplary embodiment of the wavelength tunable filter arrangement for doubling the tuning speed with the same polygon rotation speed according to the present invention. In this exemplary embodiment, the mirror surface of the polygon arrangement **24** is placed substantially a distance F2 from lens **22**, and the beam of light is reflected with a non-zero angle (rather than directly being reflected back to the telescope from the polygon arrangement's **24** mirror facet). The sweep angle of the reflected light from the polygon arrangement **24** is double the polygon arrangement's **24** rotation angle. When the incident angle difference **90** between λ_1 and λ_N with respect to the polygon arrangement **24** is approximately the same as the facet-to-facet angle **92** of the polygon, e.g., angle θ, the sweep angle **94** of the reflected light is 2θ for a rotation of the angle θ of the polygon arrangement **24**. By placing two reflectors **100**, **102**, which preferably direct the reflected beam of light from the polygon arrangement **24** back to the polygon arrangement **24**, and to the telescope (e.g., similar to the telescope **6'** of FIG. **1**B), with the angle θ between each other, twice wavelength scans from λ_1 to λ_N are achieved for the polygon rotation of the one facet-to-facet angle θ.

In FIG. **1**D which shows a fourth exemplary embodiment of the present invention, the incident angle **90** difference between λ_1 and λ_N to the polygon arrangement **24** is smaller than polygon facet-to facet angle **92**, e.g., ϕ (=θ/K, where K>1). This can be achieved by reducing the grating pitch and increasing the F**2**/F**1** ratio. In this exemplary embodiment, the filter tuning speed may be increased by factor of 2K without increasing either the rotation speed of the polygon arrangement **24** or the number of facets of the polygon arrangement **24**.

The filter tuning speed can be further increased by having the beam of light reflected multiple times by the polygon arrangement **24**. A fifth exemplary embodiment of the present invention, depicted in FIG. **1**E, is an arrangement for increasing the tuning speed by factor of 4K, where K is the ratio of angle **92** to angle **90** (K=θ/ϕ). The beam of light is reflected twice (e.g., four times round trip) by the polygon arrangement **24**, so that the sweep angle **94** of the reflected light becomes angle 4θ, and the tuning speed becomes 4K times faster. Such reflection can also be assisted with the reflection of surfaces **100**, **102**, **104**, **106** and **108**. This exemplary embodiment of the filter arrangement can be used to broaden the free spectral range ("FSR") of the filter. For example, if one of the final reflectors **102** in the embodiment shown in FIG. **1**E is removed, the FSR of the filter may become twice broader. It is likely that there is no tuning speed enhancement in such case. Similarly, it is possible to retain only one final reflector **100** in FIG. **1**E. The FSR in this embodiment can become four times broader.

FIG. **1**F shows a sixth exemplary embodiment of the present invention which provides a polygon tuning filter accommodating two light inputs and outputs. For example, in order to support two or more inputs and outputs of this filter, two or more sets of optical arrangements, each respective set including an input/output fiber **10**, **10'**, a collimating lens **12**, **12'**, a diffraction grating **16**, **16'**, and a telescope, may share the same polygon arrangement **24**. Because the scanning mirror of the polygon arrangement **24** is structurally isotropic about the rotation axis, certain optical arrangements that can deliver the beams of light to the polygon arrangement **24** can be accommodated from any directions. Since both sets of optical arrangement in the embodiment of FIG. **1**F utilize the same polygon scanner, their respective scanning optical transmission spectra are synchronized. It should be understood that the exemplary embodiment of FIG. **1**F can be extended to include multiple (greater than 2) optical arrangements each having its own input and output optical channel.

One exemplary application of the above-described polygon tuning filter according to the sixth embodiment of the present invention may be a wide band wavelength scanning light source. In FIG. **1**G which shows a seventh exemplary embodiment of the present invention, a first broadband light source **60** provides a light signal which may have a wavelength λ_1 to λ_i, and a second broadband light source **600** provides another light signal having a wavelength λ_{i-j} to λ_N. When the two optical arrangements supporting the wavelengths λ_1 to λ_i and the wavelengths λ_{i-j} to λ_N, respectively, are synchronized to output approximately the same wavelength at the same instance, such exemplary arrangement may become a wide band wavelength scanning light source with linear scan rate from λ_1 to λ_N. Since the FSR of the polygon scanning filter can be adjusted to be 200 nm or wider without any optical performance degradation, two or more broadband light sources with different center wavelengths can be combined with this filter to provide linear scanning light source over 200 nm tuning bandwidth. It should be understood that the embodiment of FIG. **1**G can be extended to include multiple (e.g., greater than 2) optical arrangements and multiple (e.g., greater than 2) broadband light sources.

The exemplary embodiment illustrated in FIG. **1**G can also be configured so that the wavelength tuning bands of each optical arrangement and broadband light source are discontinuous. In such a configuration, the tuning bands can be swept in a continuous or discontinuous sequential manner or be swept simultaneously.

FIG. **2** shows an exemplary graph of measured characteristics of the filter according to an exemplary embodiment of the present invention. The normalized reflection spectrum of the filter, e.g., a curve **48**, may be measured by using broadband amplifier spontaneous emission light from a semiconductor optical amplifier (SOA) and an optical spectrum analyzer. The optical spectrum analyzer can obtain or record a normalized throughput (reflected) spectrum in peak-hold mode while the polygon arrangement **24** spins at its maximum speed of 15.7 kHz. The measured tuning range may be 90 nm which is substantially smaller than the theoretical value of 126 nm. It is possible to have a discrepancy which may be due to an aberration of the telescope **6'**, primarily field curvature, associated with relatively large angular divergence of the beam from the grating. Such aberration can be corrected using optimized lens designs well known in the art. A curve **46** shown in FIG. **2** illustrates the throughput spectrum when the polygon arrangement is static at a particular position. The observed free spectral range is 73.5 nm, in agreement with a theoretical calculation. The FWHM bandwidth of curve **46** was measured to be 0.12 nm. The discrepancy between the measured FWHM and the theoretical limit of 0.09 nm is reasonable considering the aberration and imperfection of the optical elements.

FIG. **3** shows an exemplary embodiment of the wavelength tuning laser source according to the present invention. For example, the polygon-based filter can be incorporated into an extended-cavity semiconductor laser via a Faraday circulator **50**. Intra-cavity elements may be connected by single-mode optical fibers **10**. The gain medium may be a semiconductor optical amplifier **52** (e.g., SOA, Philips, CQF 882/e). Laser output **72** may be obtained via the 90% port of a fiber-optic fused coupler **70**. Two polarization controllers **64**, **62** can be used to align the polarization states of the intra-cavity light to the axes of maximum efficiency of the grating **16**, and of the maximum gain of the SOA **50**. A current source **54** may provide an injection current to the SOA **50**. The polygon arrangement **24** may be driven and controlled by a motor driver **97**. To generate a sync signal useful for potential applications, approximately 5% of the laser output may be directed to a photodetector **82** through a variable wavelength filter **80** with bandwidth of 0.12 nm. In this exemplary implementation, the center wavelength of the filter was fixed at 1290 nm. The detector signal can generate short pulses when the output wavelength of the laser is swept through the narrow passband of the fixed-wavelength filter. The timing of the sync pulse may be controlled by changing the center wavelength of the filter.

FIG. **4**A shows a graph of exemplary first output characteristics (laser spectrum vs. wavelength) of the laser source according to the present invention, and FIG. **4**B is a graph of exemplary second output characteristics (output power vs. time) of the laser source according to the present invention. Turning to FIG. **4**A, curve **110** represents the output spectrum of the laser measured by the optical spectrum analyzer in peak-hold mode, e.g., when the polygon arrangement spins at 15.7 kHz. The edge-to-edge sweep range was observed to be from 1282 nm to 1355 nm, equal to the free-spectral range of the filter. The Gaussian-like profile of the measured spectrum, rather than a square profile, can be mainly due to the polarization-dependent cavity loss caused by polarization sensitivity of the filter and the birefringence in the cavity. It may be preferable to adjust the polarization controllers to obtain the maximum sweep range and output power. In FIG. **4**B, curve **114** is the output of the exemplary laser in the time domain. The upper trace **112** is the sync signal which may be obtained through the fixed-wavelength filter. The amplitude of power variation from facet to facet was less than 3.5%. The peak and average output power was 9 mW and 6 mW, respectively. The y-axis scale of the curve **110** of FIG. **4**A can be calibrated from the time-domain measurement, because the optical spectrum analyzer records a time-averaged spectrum due to the laser tuning speed being much faster than the sweep speed of the spectrum analyzer.

A frequency downshift in the optical spectrum of the intra-cavity laser light may arise as the light passes through the SOA gain medium, as a result of an intraband four-wave mixing phenomenon. In the presence of the frequency downshift, greater output power can be generated by operating the wavelength scanning filter in the positive wavelength sweep direction. FIG. **5** shows an exemplary illustration of a normalized peak power of the laser output measured as a function of the tuning speed. The negative tuning speed can be obtained by flipping the position of the collimator and the orientation of the grating with respect to the optic axis **38** of the exemplary embodiment of the arrangement according to the present invention. It is preferable to make the physical parameters of the filter identical in both tuning directions. The result shows that the combined action of self-frequency shift and positive tuning allows higher output to be obtained and enables the laser to be operated at higher tuning speed as is demonstrated in the curve **120**. Therefore, the positive wavelength scan may be the preferable operation. The output power can be decreased with an increasing tuning speed. A short cavity length may be desired to reduce the sensitivity of the output power to the tuning speed. In such case, a free-space laser cavity may be preferred.

An exemplary embodiment of a free-space extended-cavity semiconductor tunable laser arrangement according to the present invention is depicted in FIG. **6**. A semiconductor waveguide **162** made on a substrate chip **160** can be coupled to the polygon scanning filter via a collimating lens **180**. The front facet **164** thereof may be anti-reflection coated, and the output facet **166** may be cleaved or preferably coated with dielectrics to have an optimal reflectivity. The laser output **190** may be obtained through the output coupling lens **182**. The sync output may be taken by using a lens **140**, a pinhole **142**, and a photodetector **144** positioned on the 0-th order diffraction path for the light which is on retro-reflection from the polygon scanner **24**. The photodetector **144** can generate a short pulse when the focus of the optical beam of a particular wavelength sweeps through the pinhole **142**. Other types of gain medium include but are not limited to rare-earth-ion doped fiber, Ti:Al_2O_3, and Cr^{3+}:forsterite. The first and second lenses **20**, **22** can be preferably achromats with low aberration particularly in field curvature and coma. The collimating lenses **180**, **182** are preferably aspheric lenses.

FIG. **7** shows another exemplary embodiment of the wavelength tunable filter which includes an input collimating lens **12**, diffraction grating **16**, focusing lens **200**, and a spinning disk **210**, as shown in FIG. **7**. The diffraction grating **16** preferably has a concave curvature that has a focal length and may thus eliminate the need for the use of the focusing lens **200**. The diffraction grating may be replaced by other angular dispersive elements such as a prism. Preferably more than one reflector **212** can be deposited on the surface of the spinning disk **210**. Preferably, the reflectors **212** may include multiple narrow stripes periodically and radially patterned. The material for the reflectors is preferably gold. The disk **210** can be made of a lightweight plastic or silicon substrate. Instead of the reflectors deposited on the top surface of the disk, the disk can have a series of through holes followed by a single reflector attached to the back surface of the disk or supported independently from the disk. Incident from the optical fiber **10**, the optical beams of different wavelengths are illuminated on the surface of the disk into a line after being diffracted by the grating **16** and focused by the lens **200**. The beam that hits the reflectors of the spinning disk may be retro-reflected and received by the optical fiber **10**. For example, a mirror **202** may be used to facilitate the access of the beam onto the disk.

The distance from the lens **200** to the reflectors of the disk **210** may be approximately equal to the focal length, F, of the lens **200**. The tuning range of the filter may be given by $\Delta\lambda = p \cos \beta_0 (D/F)$, where D denotes the distance between the stripes. The width of the strip, w, can preferably be substantially equal to the beam spot size, w_s, at the surface of the disk:

$$w_s = W\frac{\cos\beta_0}{\cos\alpha} \cdot \frac{F/z}{\sqrt{1 + f/z^2}},$$

where $z = \pi w_s^2/\lambda$. Such formulation may lead to a FWHM filter bandwidth given by $(\delta\lambda)_{FWHM}/\lambda_0 = A \cdot (p/m) \cos \alpha/W$ where $A = \sqrt{4 \ln 2}/\pi$. For $w > w_s$, the filter bandwidth may become greater, and for $w < w_s$, the efficiency (reflectivity) of the filter can be decreased by beam clipping. The orientation of the incident beam **30** with respect to the optic axis of the lens **200** and the spinning direction **220** may determine the sense of wavelength tuning. The positive wavelength scan may be preferable, which is the case of the exemplary embodiment shown in FIG. **7**.

Two exemplary applications of the exemplary embodiments of the present invention are described as follows. FIG. **8** shows a block diagram of an exemplary embodiment of the spectrally encoded confocal microscope ("SECM") that uses the aforementioned tunable laser source **300**. The basic principle of SECM has been described in detail in U.S. Pat. No. 6,341,036, the disclosure of which is incorporated herein by reference in its entirety. An exemplary probe **310** includes a transmission grating **312** provided between two silicon prisms **314**, **316**, a collimator **318**, and a microscope objective lens **320**. The probe is equipped with a micro actuator **322** to scan the beam onto a different location of the sample **330**. The actuator **322** may be driven by an actuator driver **324** at substantially slower speed than the tuning speed of the laser source. The probe motion is preferably rotary or translational and is synchronized to the sync output of the laser source. In one example, the wavelength sweep frequency may be 15.7 kHz, and the probe scan frequency can be 30 Hz, which allows 30 frames of image to be obtained in 1 second. The objective lens **320** has a nigh numerical aperture to provide a transverse resolution of an order of micrometers and a confocal parameter of a few micrometers. The focus of the optical beam may be continuously scanned in time over the sample **330** by the swept output wavelength of the optical source and the scanning motion of the probe. The optical power returned from the sample is proportional to the reflectivity of the sample within a small section where the beam was focused down to a narrow waist at a given time. Two dimensional en-face image of the sample is constructed by a signal processor **344**. The detector **340** is preferably an avalanche photodiode ("APD") followed by a transimpedance amplifier **342**. The reflected power may be received through a Faraday circulator **350** or a fiber-optic coupler.

Another exemplary application of the exemplary embodiments of the present invention is for optical coherence tomography ("OCT") the details of which are described in U.S. Pat. No. 5,956,355, the disclosure of which is incorporated herein by reference in its entirety. In one exemplary configuration, depicted in FIG. **9**, an output of a tunable source **300** may be directed to a sample **330** through a fiber-optic coupler **410**. An objective lens **412** in the probe may typically provide a focus near the surface or within the sample **330**. The reference mirror **420** can be placed in a reference arm **120** at a position where an optical path length between two arms of the Michelson interferometer is substantially matched. Alternatively, the reference path can be configured in a transmissive, nonreflective configuration. The detector **430** may be a PIN photodiode followed by a transimpedance amplifier **432** with finite frequency bandwidth. The detector may preferably incorporate polarization diverse and dual balanced detection. The detector signal can be processed in the processor **434** through a fast Fourier transform to construct the depth image of the sample. The probe may be scanned by an actuator **414** and an actuator driver **416** to allow a 3-dimensional image of the sample to be obtained.

FIGS. **10**A and **10**B show a top and perspective view of another exemplary embodiment of the wavelength tunable filter according to the present invention. An angularly deflecting optical element **700** of this exemplary embodiment can be a rotating polygon arrangement **24** where the facets of the polygon are on the inner diameter of a hollow cylinder. A dispersing element **702** such as a diffraction grating can be placed at the center of the polygon arrangement **24**. Light can be delivered to the grating through an optical fiber and collimated onto the grating so that each frequency component of the light is diffracted through a different angle (Θ). Only one narrow range of frequencies may be substantially orthogonal to one facet of the polygon arrangement **24**, and therefore such frequency range may be reflected back to the diffraction grating and collected by the optical fiber **704/706**. When the cylinder rotates, a surface normal direction for the illuminated polygon arrangement's facet may align with a new narrow frequency range. By rotating the cylinder, frequency tuning can thereby be achieved. When the cylinder rotation angle becomes large, an adjacent facet of the polygon arrangement **24** can become aligned with the light diffracted from the grating and the filter will repeat another frequency tuning cycle. The free spectral range and finesse can be controlled by appropriate choice of the polygon diameter, number of facets, collimated beam diameter and diffraction grating groove density.

The foregoing merely illustrates the principles of the invention. Various modifications and alterations to the described embodiments will be apparent to those skilled in the art in view of the teachings herein. For example, the invention described herein is usable with the exemplary methods, systems and apparatus described in U.S. Patent Application No. 60/514,769. It will thus be appreciated that those skilled in the art will be able to devise numerous systems, arrangements and methods which, although not explicitly shown or described herein, embody the principles of the invention and are thus within the spirit and scope of the present invention.

What is claimed is:

1. An apparatus comprising:

a first arrangement configured to emit an electromagnetic radiation that has a spectrum whose mean frequency changes at a rate of that is greater than about 100 terahertz per millisecond, and

a second arrangement configured to at least one of transmit or reflect at least one portion of the electromagnetic radiation based on a frequency of the electromagnetic radiation, wherein the at least one portion has a full-width-at-half-maximum frequency distribution that is smaller than about 100 GHz.

2. The apparatus according to claim **1**, wherein the second arrangement is situated on or within the first arrangement.

3. The apparatus according to claim **1**, wherein the mean frequency changes repeatedly at a repetition rate that is greater than about 5 kilohertz.

4. The apparatus according to claim **3**, wherein the mean frequency changes over a range that is greater than about 10 terahertz.

5. The apparatus according to claim **4**, wherein the spectrum has an instantaneous line width that is smaller than about 100 gigahertz.

6. The apparatus according to claim **1**, further comprising a laser resonating arrangement which forms an optical circuit and which is configured to control a spatial mode of the electromagnetic radiation, wherein the first arrangement causes the electromagnetic radiation to propagate substantially unidirectionally within at least a portion of the resonating arrangement.

* * * * *